Narrowing, Slowing and Closing the resource Loops

circular economy in the wind industry

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NARROWING, SLOWING AND CLOSING THE RESOURCE LOOPS

CIRCULAR ECONOMY IN THE WIND INDUSTRY

BY
JONAS PAGH JENSEN

DISSERTATION SUBMITTED 2018

AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

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CV

Jonas Pagh Jensen obtained his Master of Science in Environmental Management and Sustainability Science at Aalborg University in 2014 and his Bachelor's degree in Urban, Environmental and Energy Planning at Aalborg University in 2012. Jonas began his industrial PhD project in September 2014 at the Department of Planning at Aalborg University and at Siemens Wind Power (now Siemens Gamesa Renewable Energy). Jonas is currently employed as a HSE specialist by Siemens Gamesa Renewable Energy.

Papers included in the thesis (and corresponding chapter)

Paper I: Jensen, J.P., (201x). *Cost as a driver for eco-innovation in the wind industry.* Manuscript submitted to Journal of Cleaner Production, December 2017. (Chapter 5)

Paper II: Jensen, J.P., Prendeville, S., Bocken, N., Peck, D. (201x) *Creating Sustainable Value through Remanufacturing: Three Industry Cases*. Manuscript submitted to Journal of Cleaner Production, October 2017. (Chapter 7)

Paper III: Jensen, J. P**,** Remmen, A. (2017) *Enabling circular economy through product stewardship.* Procedia Manufacturing 8 pp. 377-384. (Chapter 8)

Paper IV: Jensen. J.P. (201x) *Evaluating the environmental impacts of recycling wind turbines.* Manuscript submitted to Wind Energy, February, 2018 (Chapter 9)

Paper V: Jensen, J.P., Skelton, K. (201x) *Wind turbine blade recycling; experiences, challenges and possibilities in a circular economy*. Manuscript submitted to Renewable & Sustainable Energy Reviews, October 2017. (Chapter 10)

Paper VI: Jensen, J.P., (201x). *NdFeB magnets and the wind industry. Towards circularity?.* Manuscript submitted to Journal of Cleaner Production, January 2018. (Chapter 11)

Paper VII: Jensen, J.P., Skelton, K. (201x) *B2B engagement for sustainable value (co)creation in the wind energy industry*. Manuscript submitted to Industrial Marketing Management, 2017. (Included in Chapter 12)

Other scientific presentations and publications by the author

(7) Jensen. J.P., 2017: Eco-innovation through cost-competitiveness in the offshore wind industry. Conference proceedings at 18th European Roundtable for Cleaner Production and Sustainable Consumption (ERSCP). Skiathos, Greece, 01.-05. October 2017

(6) Jensen, J.P., Skelton, K., Jones, G., Williams, S., Burnette, S., and Levine, S., 2017: From B2B communication to B2B value-adding engagement and partnerships for sustainability in the wind power sector. Poster presentation at 8th International Conference on Life Cycle Management (LCM). Luxembourg, Luxembourg, 03.-06, September 2017

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(4) Jensen, J.P, 2016: Cirkulær økonomi: Når miljøarbejdet møder forretningen. Popular scientific article published at videnskab.dk

(3) Jensen, J.P., Skelton, K., 2015: Product passport as a tool for sustainable resource use. Conference proceedings Global Cleaner Production and Sustainable Consumption (GCPSC). Sitges, Spain, 01. – 04. November 2015

(2) Guldmann, E., Jensen, J.P., 2015: Implementation of circular economy in Danish companies. Conference proceedings Global Cleaner Production and Sustainable Consumption (GCPSC). Sitges, Spain, 01. – 04. November 2015

(1) Jensen, J.P., 2015: Routes for Extending the Lifetime of Wind Turbines. Conference proceedings Product Lifetimes And The Environment (PLATE). Nottingham, United Kingdom. 17. - 19. June 2015

SUMMARY

The main focus of this research concerns the role of the circular economy concept as a means towards sustainable value creation for a manufacturer of wind turbines. The notion of circular economy was first introduced in the 1990s, but the wider adoption in academia and business has been increasing lately. The concept aims at retaining the highest possible value of a product or material for the longest possible time to minimize the resource use and increase the resource efficiency, which is also being highlighted in the UN Sustainable Development Goals.

However, multiple circular economy definitions are apparent in the scientific literature with different notions of the concept. This thesis adopts a view, where circular economy act as an umbrella concept, which is divided into three strategies being narrowing, slowing and closing of the loops. The *'narrowing loops'* is related to the concept of resource efficiency, the *'slowing loops'* is about extended use and reuse of products and material over time, through design of long lifetime and lifetime extension activities and the *'closing loops'* focuses on the recycling of the materials and ultimately focusing on eliminating 'leakages' from the system.

This research is a result of an industrial PhD project in collaboration between the research group on Sustainability, Innovation and Policy at the Department of Planning, Aalborg University and Siemens Wind Power. The main research question is:

What are the potentials of narrowing, slowing and closing the loops for Siemens Wind Power products as part of a sustainable value creation strategy?

The thesis analyzes a series of case studies related to each of the circular economy stratigies identified. The research process was guided by sub-research questions for each of the cases. In each case, different aspects of the circular economy concept within the wind industry and different methodological choices were applied. This included: observations, engaging in practice, literature and document reviews, semi-structured interviews, workshops, attending conferences, conducting life cycle assessments, external partnerships and sparring with academia and other PhD and Master's projects.

The analysis is divided into four parts outlined below and includes seven manuscripts for academic journals. Additional outcomes related to the company are: recycling guidelines for blades and magnets, a series of life cycle assessments and linked environmental self-declarations.

Part I of this thesis outlines the contextual and conceptual framework that the project is taking place within. The contextual frame represents the company and the industry

characteristics, which influenced the research. This included external conditions in the wind industry, organizational setting and product and service offerings of the company. The conceptual frame includes the analysis of circular economy as an umbrella concept, which is then broken down to three identified strategies – narrowing, slowing and closing. Each strategy is addressed in the following parts of the thesis.

Part II of this thesis addresses narrowing of the loops. This this is an integrated part of the product development process in order to minimize the cost of the turbine with the aim of lowering the levelized cost of energy. The development process of the 8MW offshore direct drive turbine was analyzed and it went through three phases being 'redesign', 'scale-up' and 'continuous improvement', where especially the redesign and continuous improvement phases were targeting narrowing the loops.

Through the case study of the development process from 6 MW to 8 MW turbines for offshore purposes, it is found that it has been possible to increase the annual energy output by 20 %, whilst maintaining the same mass, which led to an actual reduction in CO_2-eq. emissions per kWh delivered to grid from 7,1 gram to 5,8 gram as shown in this project. Further, the energy pay back time was reduced from 9,5 months to 7,6 months.

In short, the narrowing loops approach is central to lower the LCOE, which is a pre-requisite to remain competitive and at the same time, this lowers the environmental impact per kWh delivered to grid thereby contributing to sustainable value creation.

Part III of this thesis addresses how slowing the loops can be applied. In the field of service and maintenance digitalization and use of diagnostic tools based on data is driving the development. Predictive maintenance instead of reactive maintenance has been the focus in order to minimize the number of visits to the wind turbines and to schedule the maintenance and repairs to times of low wind (or low electricity prices, if no subsidy schemes are in place). This can also be applied to smart management of the turbine to e.g. reduce the loads in high wind and thereby provide the basis for extending the ***technical*** lifetime.

Lifetime extension (either on the same site or new site) is still in its infancy analyzed from the manufacturer perspective. The scientific literature indicated a small decrease in efficiency of the turbine as it ages, but an assessment of a specific turbine model showed no loss in efficiency as it ages. An assessment of a full turbine remanufacture shows that it is possible to extend the technical lifetime by replacement of central components that are prone to tear and wear. Life cycle assessments show a strong correlation between lifetime extension and environmental impact reduction in terms of CO_2-eq. emission per kWh delivered to grid.

Further, this thesis showed that by upgrading the turbine during its lifetime, the value of it increases as a more efficient turbine is now in place with higher energy output. Such modifications hold the potential to increase the ***economic and technical*** lifetime.

Part IV of this thesis addresses several aspects of closing the loops. First of all, it analyzes how other industries have supported end-of-life recycling by increasing the transparency on material data and supporting by integrating this information into central databases.

Through a case study of a 60 MW wind farm, it was found that most parts of the turbine are recyclable. However, composite material parts as well as NdFeB magnets constituted challenges and these were further researched. The assessment could act as a basis for setting requirements or targets for recyclability of wind farms. It was found that by recycling the wind farm with best available technologies 81,36GJ of energy was saved by re-introducing the materials into the market compared to primary materials as well as 7351 ton of CO_2-eq.

Composite material continues to be the preferred material among wind turbine blade manufacturers for blade production. The findings from the GENVIND project show that closed loop recycling of these materials is not expected in the short-term future under current waste legislation scenarios. The recoverable materials have a too low value compared to the cost of extracting these – although technical possible. However, the project also showed that utilizing the properties of the product or material can be beneficial. The dream of closed-loop recycling and upcycling is not assessed realistic at the moment in larger scale, when dealing with composite materials.

The study found that NdFeB magnets had improved significantly in performance during the time of the study. Further, the study showed that the magnets are big in size, large volumes are present and they are dismountable. Further, the salvage value, at the time of study, was 11-12 USD/kg. The cost of demagnetizing, dismantling and transporting constituted approximately one third of this. Life cycle assessment showed that by recycling the NdFeB magnets, production steps requiring large amounts of acid and energy could be avoided thereby 'short-tracking' the production loop and having magnets with less impact as an outcome. Closed-loop reuse for new turbines is however not possible due to design requirements.

Wind energy constitutes one of the more attractive renewable energy options in terms of price, environmental impacts and sustainable value creation is possible by addressing the circular economy principles. This thesis had a narrow focus on the turbine itself, and this could be expanded to include e.g. sub-structures, modes of transport, electrification of the energy system and storage solutions in to allow further integration of wind energy in conjunction with service concepts of these.

RESUMÉ

Hovedfokus for dette forskningsprojekt omhandler den rolle, som cirkulær økonomi spiller, som et middel til bæredygtig værdiskabelse hos en vindmølleproducent. Begrebet cirkulær økonomi blev første gang introduceret i 1990'erne, mens den bredere spredning i akademisk og forretnings-sammenhæng er vokset i den seneste tid. Konceptet sigter mod at opretholde den højest mulige værdi af et produkt eller materiale i den længst mulige tid for at minimere ressourceanvendelsen og øge ressourceeffektiviteten, hvilket også fremhæves i bl.a. FNs verdensmål for bæredygtig udvikling.

Der er ikke én standarddefinition for cirkulær økonomi, og flere definitioner af cirkulære økonomi-begrebet fremgår i den videnskabelige litteratur. Denne afhandling tager en tilgang, hvor cirkulær økonomi-begrebet fungerer som et paraply-koncept, der opdeles i tre strategier; *'indsnævring af kredsløb'*, *'forsinkelse af kredsløb'* samt *'lukning af kredsløb'*. 'Indsnævring af kredsløb' er relateret til ressourceeffektivitet. 'Forsinkelse af kredsløb' handler om øget brug og genanvendelse af produkter og materiale over tid blandt andet via lang levetid eller levetidsforlængelsesaktiviteter. 'Lukning af kredsløb' fokuserer på genbrug af materialer, og i sidste ende fokuserer på at eliminere "lækager" fra systemet.

Denne forskning er et resultat af et industrielt ph.d.-projekt i samarbejde mellem Forskningsgruppen for Bæredygtighed, Innovation og Politik ved Institut for Planlægning, Aalborg Universitet og Siemens Wind Power (nu kendt som Siemens Gamesa Renewable Energy). Hovedforskningsspørgsmålet i afhandlingen er:

Hvad er mulighederne for at indsnævre, forsinke og lukke kredsløbene for Siemens Wind Power' produkter, som led i en strategi for bæredygtig værdiskabelse?

Afhandlingen analyserer en række casestudier relateret til hver af de identificerede strategier for cirkulær økonomi. Forskningsarbejdet blev guidet af en række underforskningsspørgsmål tilknyttet hvert af case studierne. Case studierne analyserede forskellige aspekter af den cirkulære økonomi relateret til vind-industrien, og forskellige metodologiske valg blev anvendt. Dette omfattede: observation, deltagelse i praksis, litteratur og dokument-gennemgang, semi-strukturerede interviews, workshops, deltagelse i konferencer, livscyklusvurderinger, eksterne partnerskaber og sparring med universitetet samt andre ph.d.- og masterprojekter.

Analysen er opdelt i fire dele, som er skitseret nedenfor, og indeholder syv manuskripter indsendt til videnskabelige tidsskrifter. Yderligere resultater i

virksomhedsregi er: genanvendelsesretningslinjer for vinger og magneter, en række livscyklusvurderinger og tilknyttede miljøangivelser.

Del I af afhandlingen skitserer den kontekstuelle og konceptuelle ramme, hvori projektet tager sit udspring. Den kontekstuelle ramme repræsenterer virksomhedens og branchens karakteristika, som har indflydelse på forskningsprojektet. Dette omfatter eksterne forhold i vind-industrien, organisatoriske rammer og produkt- og serviceydelser fra virksomheden. Den konceptuelle ramme tager udspring i analysen af cirkulær økonomi, som et paraplykoncept, hvor der efterfølgende sondres mellem de tre identificerede strategier – indsnævring, forsinkelse og lukning af kredsløb. Hver af strategierne behandles i de følgende dele af afhandlingen.

Del II af afhandlingen omhandler indsnævring af kredsløbene. Dette er en integreret del af produktudviklingsprocessen for at minimere omkostningerne ved vindmøllen med det formål at sænke de samlede energiproduktionsomkostninger. Udviklingsprocessen for 8MW offshore-direkte-drev-møllen blev analyseret, og det blev vist, at denne gennemgik tre faser; "redesign", "opskalering" og "kontinuerlig forbedring", hvor især faserne ’redesign’ og ’kontinuerlig forbedring’ havde positive bidrag i forhold til at øge ressourceeffektiviteten og indsnævre kredsløbet.

I casestudiet af udviklingsprocessen fra 6MW til 8MW møller til offshore, blev det konstateret, at det har været muligt at øge den årlige energiproduktion med 20%, med i det store hele at bibeholde det samme materialeforbrug, hvilket førte til en reduktion af CO_2- ækv. emissioner pr. kWh leveret til nettet fra 7,1 gram til 5,8 gram., som det blev påvist Endvidere blev energitilbagebetalingstiden reduceret fra 9,5 måneder til 7,6 måneder.

Kort sagt er indsnævring af kredsløbet i form af øget ressourceeffektivitet centralt for at sænke produktionsomkostningerne fra vindenergi, hvilket er en forudsætning for at forblive konkurrencedygtig og samtidig sænke miljøpåvirkningen pr. kWh leveret til nettet, hvorved der bidrages til en bæredygtig værdiskabelse.

Del III af afhandlingen omhandler forsinkelse af kredsløb. På service-/vedligeholdelses-området er digitalisering, og brug af diagnostiske værktøjer baseret på data helt centrale for udviklingen. Forebyggende vedligeholdelse i stedet for reaktiv har været i fokus i forsøg på at minimere antallet af besøg til møllen, samt planlæggelse af vedligehold og reparation til tidspunkter med lav vind (eller lave elpriser, hvis der ikke er tilskudsordninger). Den generelle tendens er i retning af smart planlægning og optimering. Digitalisering kan også anvendes til smart styring af møllen til f.eks. at reducere belastningerne ved høj vind, og derved danne grundlag for at forlænge den ***tekniske levetid.***

Levetidsforlængelse af møllen (enten på ny eller samme lokation) er stadig relativ nye koncepter set fra producentens perspektiv. I den videnskabelige litteratur blev der påpeget et fald i effektiviteten af møllen med alderen, hvorimod en empirisk analyse af en specifik turbine-model viste ingen tab i effektivitet, som alderen steg. En vurdering af en fuld mølle-istandsættelse viste, at det er muligt at forlænge den ***tekniske levetid*** ved udskiftning af centrale komponenter, der er særdeles udsat for tæring og slid. Livscyklusvurderinger vist en stærk sammenhæng mellem levetidsforlængelse og miljøpåvirkning i forhold til CO_2- ækv. emissioner pr. kWh leveret til nettet.

Desuden dokumenteres det i afhandlingen, at ved at opgradere turbinen i løbet af dens levetid, øges værdien af møllen, da den dermed får en højere energiproduktion. Sådanne ændringer har potentialet til at øge den ***økonomiske eller tekniske levetid***.

Del IV i afhandlingen adresserer flere aspekter ved lukning af kredsløbet. Først analyseres det, hvordan andre industrier har støttet genbrug ved at øge gennemsigtigheden af materialedata, og støtte ved at integrere disse i centrale databaser til support ved endt levetid.

Gennem et casestudie af en 60 MW vindmøllepark blev det konstateret, at de fleste dele af turbinen er genanvendelige. Kompositmaterialerne samt NdFeB-magneter udgjorde imidlertid udfordringer, og disse blev yderligere undersøgt. Vurderingen kan danne grundlag for fastsættelse af krav eller mål for genbrug af vindmølleparker. Det blev konstateret, at ved genbrug vindmølleparken med den bedste tilgængelige teknologi blev 81.36GJ energi sparet ved at genindføre materialerne på markedet i forhold til primærmaterialer samt 7351 tons CO_2-ækv. blev sparet.

Kompositmateriale er fortsat det foretrukne i forhold til vindmøllevinger. Resultaterne fra projektet viste, at genanvendelse af disse materialer ikke forventes på kort sigt med de nuværende scenarier for affaldslovgivning. De genindvendte materialer har for lav værdi i forhold til omkostningerne ved genindvinding af disse - selvom det er teknisk muligt. Projektet viste imidlertid også, at udnyttelse af de tekniske egenskaber af produktet eller materialet (styrke, udholdenhed etc) kan være gavnligt i genanvendelsessammenhæng. Drømmen om genanvendelse i lukket kredsløb vurderes dog ikke realistisk for nuværende i større målestok, hvad angår kompositmaterialer.

Yderligere viste en analyse, at NdFeB-magneternes egenskaber var forbedret signifikant i løbet af PhD projektets tidsramme. Magneterne i vindmøllerne er store, der er store mængder tilstede, og de er demonterbare. Endvidere var værdien af de udtagne magneter på tidspunktet for undersøgelsen 11-12 USD / kg. Omkostningerne til afmagnetisering, demontering og transport udgjorde ca. en tredjedel af dette. En livscyklusvurdering viste, at ved at genbruge NdFeB-magneterne kan produktionstrin, der kræver store mængder kemikalier og energi undgås, hvorved miljøpåvirkningerne fra produktionsprocessen formindskes, og resultatet er magneter af genanvendt materiale med forbedret miljøprofil. Direkte genanvendelse af magneterne i nye møller er imidlertid ikke muligt på grund af skrappe designkrav.

Vindenergi udgør en attraktiv, vedvarende energikilde hvad angår pris og miljøpåvirkning, og bæredygtig værdiskabelse er mulig ved at følge principperne for den cirkulære økonomi. Denne afhandling har haft et snævert fokus på selve vindmøllen, og dette kunne fremtidigt udvides til at omfatte hele installation inkluderende fundamenter, kabler og transportformer ligesom større anliggender som elektrificering af energisystemet og lagringsløsninger for at muliggøre yderligere integration af vindenergi i energisystemet –samt servicekoncepter til vedligehold og optimering af disse – kan være relevante at inddrage i analysen.

PREFACE AND ACKNOWLEDGEMENTS

This PhD thesis is written as part of a three-year industrial PhD fellowship in collaboration between Siemens Wind Power and the Sustainability, Innovation and Policy research group at the Department of Planning at Aalborg University. I began the PhD studies in September 2014 and the thesis was finalized in February 2018. During the studies, I had 10 weeks of paternity leave.

During my studies in M.Sc. in Environmental Management and Sustainability Science, I found the interest in researching the link between private companies and how circular economy could apply to their reality and what value it could bring. As my Master's thesis, I had the opportunity to begin researching this topic, by assessing how the use of rare earth permanent magnets in the wind turbines could fit into a circular economy – a topic that was carried on into this thesis.

The thesis is article based supplemented by chapters written solely for the purpose of the PhD thesis. Chapters 5 and 7-12 comprise papers (submitted or accepted). Chapter 3 is co-written with another PhD candidate, Chapter 6 is a continuation of a conference paper and the remaining chapters are solely written for and published in this PhD thesis.

The PhD research project was financed partly through Innovationsfonden's Industrial PhD program (grant no. 4135-00046) as well as by Siemens Wind Power. As part of the PhD project, active collaboration with the GENVIND project and the Rethink Resources project – both to be described later - were carried out.

This research process has been a multi-disciplinary and multi-methodological journey, where many stakeholders have played a crucial role. It has been a ride with ups, downs and unexpected turns. Throughout this process, I have been reflecting on various issues, methodological choices and project ideas. The process have been involving many people without whom I would never have been able to succeed this project.

Being an industrial PhD fellow includes wearing several 'hats' throughout the project – e.g. researcher, specialist, colleague, etc, and often it's necessary to stop up and reflect on the main objective of the PhD project. In such a setting, the experience, the people in the vicinity of this project has been highly appreciated and I am grateful for the guidance provided throughout the project.

Therefore, I would like to thank my main supervisor at Aalborg University, Professor Arne Remmen, for his invaluable commitment to this project. I appreciate your dedication to the topic, your easy-going person and cosy experiences we have had during the project. A thank also goes to Professor Han Brezet, for his feedback, for introducing me to parts of his enormous network and for opening the doors of TU Delft, where I met many great people, had interesting discussions and learned to survive the biking madness in the mornings to the University. A thank to Tine Herreborg Jørgensen (now Head of the Department of Planning at the Technical Faculty of IT and Design at Aalborg University), who initiated the project from the company side and helped me take my ‘research baby steps’ in the beginning of the project. Moreover, a thanks to the research group and all it’s members during the project.

From the company side, I would like to thank several people. Kristen Skelton, for being my company supervisor, with whom I have spent hours discussing the topic on mutual journeys towards completion of both our PhD projects. A special thank also to Karin Borg for supporting the project, giving access to the internal network in the company and in trusting me to explore the field of circular economy within the company. Further, a thank to all my colleagues from the department, who let me into their daily routines and treated me as a part of the team and all other colleagues, who supported, took time to discuss, questioned or even challenged the project – I think you all have a share in this.

Also thanks to family and friends for the support in the process and my utmost thank goes to my support at home, Anne. You have been a huge support in this process, have tried to act interested even when I became too nerdy. You and Astrid were good at reminding me of other important parts of life.

Aarhus, February 2018
Jonas Pagh Jensen

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LIST OF ABBREVIATIONS

Below, a list of abbreviations (sorted in alphabetical order)

B - Boron

B2B – Business-to-Business

CE – Circular Economy

CO_2 – Carbon dioxide

Cr - Chromium

DFS – Design for Sustainability

Dy - Dysprosium

EEE – Electrical and electronic equipment

EHS – Environment, Health and Safety

EPD – Environmental Product Declaration

EWEA – European Wind Energy Association

Eq. . Equivalent

GJ - Gigajoule

GWEC – Global Wind Energy Council

IEA – International Energy Agency

IRENA – International Renewable Energy Agency

ISO – International Organization for Standardization

KPI – Key Performance Indicator

kWh – Kilo watt hour

LCA – Life cycle assessment

LCOE – Levelized cost of energy

MJ – Megajoule

MW - Megawatt

MWh - Megawatt hour

Nd - Neodymium

NdFeB – Neodymium-Iron-Boron

OEM – Original Equipment Manufacturer

O&M – Operation and maintenance

PE – Polyethylene

PP – Polypropylene

PVC - Polyvinylchloride

RQ – Research Question

SAG – Siemens AG

SCADA - Supervisory Control And Data Acquisition

SCOE – Society's cost of energy

SGRE – Siemens Gamesa Renewable Energy

SLCA – Social Life Cycle Assessment

SWP – Siemens Wind Power

TWh – Terawatt hour

Yr – Year

WEEE – Waste of electrical and electronic equipment

1. INTRODUCTION

1.1 THE EARTH AS A CLOSED SYSTEM

In 1966, Boulding argued that '*The Earth is a closed system and, with the exception of energy, the resources available are constant*, meaning that the natural environment has a certain assimilative capacity to handle waste (Boulding, 1966). This was later supported by Meadows et al. (1972) 'Limits to Growth' et al). In 2009, Rockström et al. argued that we exceed this capacity on certain parameters, which elicited the introduction of their Planetary Boundaries concept.

'Anthropogenic pressures on the Earth System have reached a scale where abrupt global environmental change can no longer be excluded.' (Rockström et al., 2009)

The planetary boundaries are not a roadmap for sustainable development but an attempt to identify biophysical boundaries at the planetary scale within which humanity has the flexibility to choose a myriad of pathways for human well-being and development. Rockström et al. (2009) state that further work will need to focus on the societal dynamics that have led to the current situation and propose ways in which our societies can stay within these boundaries. (Rockström et al., 2009)

'Planetary boundaries define, as it were, the boundaries of the "planetary playing field" for humanity if we want to be sure of avoiding major human-induced *environmental change on a global scale.'* (Rockström et al., 2009)

Part of a 'roadmap' was later suggested by the World Bank in 2012, which argues that perhaps the most important transformation for the sustainable development trajectory is the shift towards a low-carbon economy. If this does not happen it '*…would expose all countries to catastrophic climate change, including sea level rise, ocean acidification, extreme storms, droughts, floods, crop failures, and the collapse of whole ecosystems.'* (World Bank, 2012)

Most of the reduction efforts must occur in the energy sector, which accounts for the bulk of greenhouse gas emissions. (Rockström et al., 2013) Among the key elements in the reductions of greenhouse gas emissions is *'…(ii) almost CO2-free electricity generation by 2050 using a balance of renewables (essentially wind, solar), nuclear and carbon capture storage*.' (Rockström et al., 2013)

Ecological limits cannot be extended through technological means but technological innovations can increase the eco-efficiency of products and services and thus enable larger quantities of these to be produced and consumed within ecological limits (Robinson, 2004). Bjørn et al. (2017) address that companies' attention has shifted to the topic and how the concept of planetary boundaries can potentially influence product portfolio changes, particularly fossil fuels. They also emphasize the need for new types of green tech-related products and services and allude that their supply will eventually grow. This means that the concept of ecological limits can be expected to influence different types of companies' product portfolios. (Bjørn et al., 2017)

In the light of this, the recognition of the limits to planetary resource and energy use, and the importance of viewing the world as a “system”, where pollution and waste are viewed as a defeat, lay at the foundations of circular economy thinking. (Bocken et al., 2016)

1.2 A SUSTAINABLE CIRCULAR ECONOMY?

This industrial PhD seeks to address these topics and takes it departure in the scientific literature within two fields: *design and innovation for sustainability* as well as *circular economy and the closing of material loops* and the application of these in the wind industry sector.

Scientific literature is significant within the two research fields but only few investigations have combined the knowledge from both fields:

Design and innovation for sustainability is in line with the literature that has addressed environmental impacts associated with industry and has especially placed emphasis on possible solutions such as pollution prevention, cleaner production, clean tech, waste minimization, eco-design and design for sustainability (DfS) (Mont, 2002).

The scientific literature on DfS addresses a broader set of dimensions, including economic, social and environmental parameters. It also highlights the on-going changes in innovation processes: from being technology- towards people-oriented (employees, customers, etc); moving from single product development departments towards a more cross-functional and integrated organization; from having an insular focus on the interest of the company towards more systemic and societal attention. (Porter & Kramer, 2011; Network for Business Sustainability, 2012)

The environmental initiatives within enterprises have gradually expanded from optimization of production towards a broader attention to the environmental performance of products (Remmen 2001). Environmental considerations in product development are an integrated part of several companies’ environmental concerns as the product combine current markets, technology trends and regulatory demands into new product features (Johansson, 2002). Such considerations are crucial and must be implemented throughout the value chain to gain efficiency increases. For example, supply chain considerations are essential to enable innovations such as the sustainable sourcing of raw materials and components. To develop sustainable products requires engaging in partnerships throughout the complete supply chain (Nidumolu et al., 2009).

Circular economy and the closing of material loops has gained attention both in the scientific community and among enterprises. The industrial system has been based on a linear model of resource consumption that follows a 'take-make-dispose' pattern, which has meant significant growth in global resource use and led to predications in the rise of raw material prices. (OECD, 2013) Circular economy has been proposed as one way of adapting to new demands from both customers and legislation.

The circular economy aims at systematically designing out waste of materials to improve the efficiency of the overall material chain. Designing for a circular economy can mean improvements in material selection and product design as well as innovative business models. (Ellen MacArthur Foundation, 2013) Pearce and Turner (1990) were among the first to introduce circularity as a notion in 1990 (Anderson, 2006), which was built on former concepts such as industrial ecology (Frosch & Gallopoulos, 1989), life cycle thinking, Cradle-to-Cradle design (McDonough Braungart Design Chemistry, 2012) and the performance economy (Stahel, 2010). Within the field of industrial ecology, several research projects have studied the flow of resources and materials in industrial systems and methodologies have been developed such as material flow accounting, life cycle assessment, etc. (Frosch & Gallopoulos, 1989; Allenby, 2006; Huppes & Ishikawa, 2011). These studies create a platform for understanding the potentials and pitfalls of closing material loops. Bocken et al. (2016) divide the circular economy into three categories being narrowing, slowing and closing the resource loop and frames a series of archetype business models that can support each of the categories (see chapter 4).

1.3 NARROWING, SLOWING AND CLOSING

The 'narrowing loops' strategy is related to the concept of resource efficiency, which has also successfully been applied within a linear business model. Existing strategies for resource efficiency can be used in conjunction with both product life extension and recycling within a circular system. (Bocken et al., 2016) In general, it relates to creating products and services that provide consumers with (at least) the same level of performance but also with a lower environmental burden. The transition to more resource efficient production and consumption is also supported by e.g. the European Commission's 'Roadmap to a Resource Efficient Europe' (European Commision, 2011) and scientific networks such as the European Roundtable of Sustainable Consumption and Production (ERSCP). The 'Roadmap to a Resource Efficient Europe' outlines the need for a fundamental transformation of production and consumption and involves a 4-10 fold increase in resource efficiency. Furthermore, it highlights the case of resource efficiency as a driver for greater competitiveness and profitability. (European Commision, 2011)

The 'slowing loops' strategy is about extended use and reuse of products and material over time, through design of long lifetime and lifetime extension activities. Extending the lifetime of products is assessed to reduce the environmental impacts compared to new products as production and distribution can be postponed and waste amounts are being reduced. (van Nes & Cramer, 2006). However, in some cases – often energy using products – substitution might at some point in time be appropriate seen from a life cycle assessment perspective, if the new generation products offer significant energy savings compared to the older generation. (Bakker et al, 2014) Further, extending the lifetime of a product and circulating the materials can generate revenue. (Pocock et al., 2011). A sustainable product design can drive the development of circular opportunities by securing the best technical options of maintenance, upgrade or reuse e.g. through the concepts of Eco-design or Design for Sustainability. (Ardente et al., 2012)

Bocken et al. (2016) note that 'narrowing' and 'slowing' could be the same (less resources flowing through the system) but highlight that slowing invokes a different relationship with time, whereas narrowing accepts the speed of the resource flows. (Bocken et al., 2016) This is highlighted as one of the pitfalls of the narrowing strategy as it does not address the time dimension, so if the resource efficiency is outpaced by the total flows, the overall savings from a system perspective are non-existing. Organic textiles in fast fashion can be mentioned as one example of this.

The 'closing loops' strategy focuses on the recycling of the materials and ultimately focusing on eliminating 'leakages' from the system (Ellen MacArthur Foundation, 2013). Historically, the interest in circular economy has been related to closing the outer loop of materials e.g. through industrial symbiosis. (Mathews & Tan, 2011)

The three strategies introduced above are further expanded on in chapter 4.

1.3.1 SUSTAINABLE VALUE CREATION

The business models to support the circular economy e.g. Product Service Systems – providing utility to customers through the use of services – as a possible strategy for dematerialization and for meeting the sustainability challenge (Spangenberg et al., 2010). The role of services in providing value is becoming increasingly important. Until recently, most of a product's added value came from the production processes that transformed raw materials into products but today value is added by services related to the product as well. Therefore, there is an increased interest among manufacturers in adding value through the provision of services that extend the spectrum of their products (Boehm & Thomas, 2013). Implementing sustainable services can require changes in business models compared to just selling the products (due to a potential change in supply chain), which can hinder such a change and thereby hamper broad implementation (Tukker, 2013).

The departure point for this PhD is that more thorough research is needed to secure a sustainable outcome of integrating DfS and services in the business model. However, in doing so an additional level of complexity is added and solutions are less clear cut (Spangenberg et al., 2010) This system does not deliver sustainable bonuses by definition as it requires great attention to the value chain (Tukker, 2013). On the other hand, the reported sustainability potentials are numerous (reference) when expanding the focus from product sale to service systems and new business models, since this allows possibilities related to durability, repair-ability, modular design, product-take back, refurbishment, leasing, etc.

In the wind industry, Siemens Wind Power (SWP) experiences an increasing quantity of customer requests related to recycling and reusability. At the outset of this PhD project, the company had begun to consider how to address the increasing demands from customers and authorities. The company had mainly formulated production related KPIs to reduce energy and waste and was in final the stages of publishing the results of its first life cycle assessments (one for each turbine platform). The aim of this is to provide input for defining product related key performance indicators (KPIs), which can support the strengthening of life cycle thinking and closing the material loops internally in the organization. The hypothesis is that SWP can achieve economic, environmental and social benefits by addressing this.

1.4 THE MAIN RESEARCH QUESTION

The overall research question for this project is:

What are the potentials of narrowing, slowing and closing the loops for Siemens Wind Power products as part of a sustainable value creation strategy?

The aim of the project is to address the strategies of ***narrowing, slowing and closing*** in the wind industry building on case studies. Circular business models and partnerships are important means in this regard, combined with sustainable innovations that are covering process optimization, product innovations and circular business models through partnerships.

The overall objective of the PhD project is to expand the scientific knowledge regarding how circular initiatives can be integrated in the overall business strategies as well as through sustainable designs and innovations in both products and services.

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2. RESEARCH DESIGN AND METHODOLOGY

The research design, theoretical approach and data collection methods of this PhD project are presented in this chapter. However, methodology sections are also included in the separate papers describing more detailed the methodological approach for each study. This chapter introduces the process of developing the PhD project with overall reflections on research design, research strategy, data collection methods and validity of the study.

2.1 THE OUTSET OF THE PHD PROJECT

The initial PhD project plan was co-developed between Aalborg University, Siemens Wind Power and the author of this thesis. The initial project plan was formulated based on the challenges Siemens Wind Power experienced at the given time. The plan was divided into five work packages, which included:

- Analysis of the potentials for ***reducing and recycling rare earth elements*** in wind turbines;
- ***Investigation of product lifetime*** of wind turbines due to the technology shift and improved service system;
- ***Development of key performance indicators for product innovation and closing material loops*** as part of design for sustainability;
- ***Engagement of designers and product developers*** in design for sustainability through participation and experiments;
- ***Assessment of unfolding business potentials*** by establishing internal and external ***partnerships to increase resource efficiency and close material loops.***

However, throughout the process there were changes to the original project plan, which are reflected in the final project structure. This is described and illustrated below. The changes are a reflection of current challenges of the company, the challenge in remaining flexible to remain relevant and the changing nature of a business environment. The process shows that some of the original work packages were either reframed or managed in a different way than originally intended. The following section will explain how the final structure of the project emerged.

2.2 PROJECT STRUCTURE

The thesis is structured in several parts and the structure can be seen in Figure 1. Below is an outline of the different parts of the thesis, with a brief description of each chapter and its relevance to wind power and the circular economy.

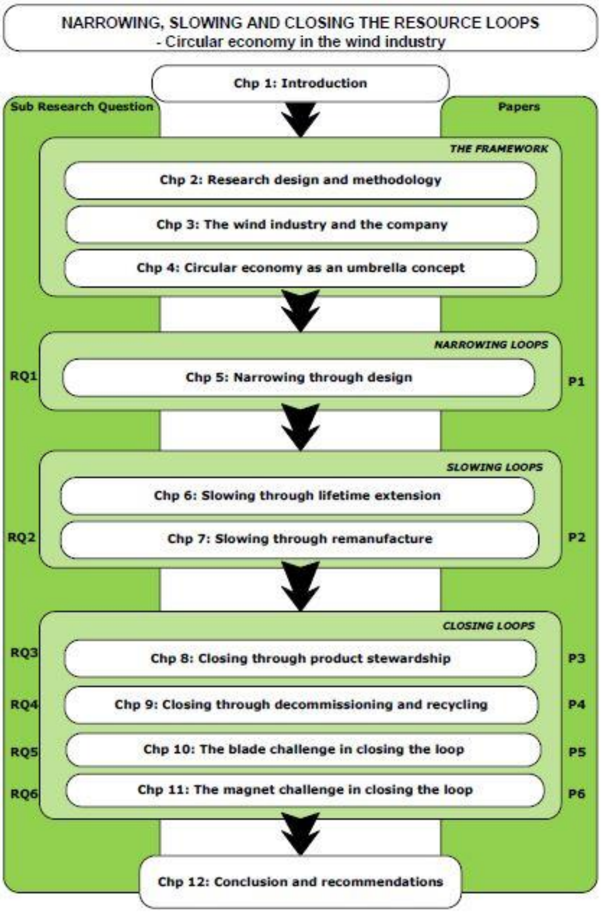

Figure 1: Illustration of the project structure divided into different parts. Further, research questions that are answered in the connected papers and chapters. (Own illustration)

Chapter 1 introduces the thesis and outlines the problem field of the industrial PhD project. Research shows how we are exceeding our ‘Planetary Boundaries’ and a range of actions have been identified to address this. In the transition to a low carbon economy, wind energy has been identified as central energy source in future energy systems, while the circular economy proposes a framework that potentially can be applied to manage the wind turbines using a life cycle perspective.

Part I consists of chapters 2-4 and represents the contextual and conceptual framework of the thesis. **Chapter 2** presents the research design and data collection methods. **Chapter 3** introduces the wind industry and the company, Siemens Wind Power, as the applied case of the PhD project. **Chapter 4** introduces the circular economy and explains how it is used as an umbrella concept to guide the research of this project and structure the thesis.

Part II consists of **Chapter 5**, which addresses the *'narrowing loop strategy.'* The chapter, which is a journal paper, focuses on the innovation journey in the design of large offshore wind turbines. Moreover, it analyses drivers for the development and applies a life cycle assessment to calculate the impact of upscaling the wind turbine in terms of resource efficiency and other environmental impacts.

Part III consists of chapters 6-7 and addresses the *'slowing loop strategy*. **Chapter 6** touches upon the increasing focus on service models as an integral part of the wind power business. Further, it addresses the technical potential of lifetime extension of a wind turbine reaching its design lifetime and evaluates the environmental impact of lifetime extension. **Chapter 7** relates to the remanufacturing as a strategy towards circular economy. It addresses cases of remanufacturing activities highlighting three different cases (sectors and products) of remanufacturing activities and highlights the need for integrating these activities into the business model of the company.

Part IV consists of chapters 8-11 and focuses on the *'closing loop strategy'*. **Chapter 8** consists of a paper that analyses how other industries have approached closing the material loop. It promotes data sharing across the value chain and the need for material documentation. **Chapter 9** focuses on the outer circle (see chapter 4) of the circular economy in the wind industry, where the decommissioning and recycling of wind turbines is investigated. Further, it estimates the environmental impact of recycling a 60 MW wind park. Chapter 10 and 11 provide a deeper analysis through the investigation of two specific turbine components (rotor blades and magnets) that are assessed as critical in terms of closing the loop. **Chapter 10** contains a paper on blade recycling, and analyzes the challenges and potentials related to blade recycling through the GENVIND innovation consortium, to which the author participated and co-developed a customized circular economy framework. **Chapter 11** is a paper on how permanent magnets are used in the wind turbine, their associated environmental impacts and how Siemens Wind Power has sought to improve these through a life cycle perspective. This chapter addresses both the 'narrowing' and 'closing' of the loop.

Chapter 12 discusses, synthesizes and concludes the findings of 'narrowing, slowing and closing the loops'. Recommendations for further actions and research are also contained in this chapter.

2.3 RESEARCH DESIGN

The aim of the overall analysis is to answer the research question:

What are the potentials of narrowing, slowing and closing the loops for Siemens Wind Power products as part of a sustainable value creation strategy?

A range of sub-questions are formulated, which guide four parts of the project and support in answering the main research question.

Part I establishes a framework to guide the analysis of the company in a circular economy. This is done through a two-folded approach: 1) understanding the company *(the contextual frame)* and 2) understanding the concept of circular economy (*the conceptual frame*).

Part II of the thesis focuses on the '*narrowing loops strategy'* to analyze *what type of value creation narrowing loops* can contribute to. The emphasis is on understanding the development trends, when realizing, in the contextual frame, that the size of the turbines is increasing. The research sub-question that guides this analysis is:

'What characterizes the design and product development of offshore turbines? Can innovations lead to narrowing of the loops and less environmental impacts?

Data collection methods for this part consisted of document and literature reviews and modelling of life cycle assessments for the 7 MW and 8 MW turbine models. Narrowing the loops does not address circularity, but resource efficiency and source reduction is part of the perception of circular economy in this thesis as part of a sustainable value creation strategy

Part III of the thesis focuses on the '*slowing loops strategy* where emphasis is on analyze *how lifetim*e *extension of wind turbines through servitization and remanufacturing can drive sustainable value creation in Siemens Wind Power?*

This is including a chapter providing a general overview of the concepts, and an evaluation of the technical potential of lifetime extension as well as an assessment of the environmental impact related to lifetime.

Further, a journal paper was made, where the research sub-question that guides the analysis is:

'Can an integrated perspective drive sustainable value creation in remanufacturing contexts?

Data collection methods for this part included document and literature review, interviews and screening lifecycle assessments.

Part IV of the thesis focuses on *'closing loops'*, where the emphasis is on addressing the *potentials of closing the loops in terms of sustainable value creation?* This is addressed through several manuscripts with different applications, which are described below.

Chapter 8 is guided by the sub-research question:

Which strategies has been taken by the automotive, shipping and aviation industry to address end-of-life challenges? What lessons can the wind industry learn from a benchmark with these industries?

This chapter investigates how other industries have approached end-of-life challenges. Data collection methods for this part included document and literature review as well as collaboration in an external research project, Rethink Resources, where external partners contributed to this analysis with expert know-how.

Chapter 9 is guided by the sub-research questions:

'How does the decommissioning process of wind turbines work? What is the environmental impact of recycling the materials at end-of-service-life?'

This chapter investigates how the decommissioning of offshore wind turbines is being carried out and assesses the environmental impact of bringing the turbine materials back into the loop. The main data collection methods for this were document and literature reviews supported by a Master's thesis on the topic, which was run as an internal project in collaboration with Aalborg University and Siemens Wind Power.

Chapter 10 and 11 provide a deeper analysis into the closing of two specific parts of the turbine – the blades and the magnets.

Chapter 10 is guided by the sub-research questions:

What are the processes for handling blades at end-of-life? What are the potential applications for secondary use?

A range of methods were used for this study; document and literature review, an internal Master's thesis project between Siemens Wind Power and University of Southern Denmark. Further, an external project, GENVIND, that included 17 companies and research institutions, which tested several applications for secondary use and finally, this was supplemented by a week of manufacturing blades in the production to get to understand the composition of the blades and the process of manufacturing these.

Chapter 11 is guided by the sub-research questions:

How has the challenge of rare earth elements in permanent magnets in the wind turbine industry been addressed? Can strategies for end-of-life benefit both the environment and the economy?

Again, several methods were used; document and literature reviews, an internal project bachelor's thesis project, internal interviews. Further, an external project (Rethink Resources), where experts from Danish Technological Institute participated and practical testing of demagnetization methods and dismantling of the magnets from the generator in collaboration with waste handlers.

Table 1: Overview of the chapters, research questions guiding the analysis and the data collection methods applied.

	Sub-research questions	**Data collection methods**
Part II – Narrowing – Chapter 5	*'What characterizes the design and product development of offshore turbines? Can innovations lead to narrowing of the loops and less environmental impacts?'*	• Document and literature review • Life cycle assessment • Internal project *(A.Bonou)*
Part III - Slowing - Chapter 7	*'Can an integrated perspective drive sustainable value creation in remanufacturing contexts?*	• Document and literature reviews • Interviews • Life cycle assessment
Part IV – Closing – Chapter 8	*Which strategies has been taken by the automotive, shipping and aviation industry to address end-of-life challenges? What lessons can the wind industry learn from a*	• Document and literature reviews • External project *(Rethink resources)*

	benchmark with these industries?	
Part IV – Closing – Chapter 9	*'How does the decommissioning process of wind turbines work? What is the environmental impact of recycling the materials at end-of-service-life?'*	• Document and literature reviews • Internal project *(R. Nommik & K. Spyridoula)*
Part IV – Closing – Chapter 10	*What are the processes for handling blades at end-of-life? What are the potential applications for secondary use?*	• Document and literature reviews • External project *(GENVIND)* • Internal project *(C.Gleitsmann)* • Manufacturing blades
Part IV – Closing – Chapter 11	*How has the challenge of rare earth elements in permanent magnets in the wind turbine industry been addressed? Can strategies for end-of-life benefit both the environment and the economy?*	• Document and literature reviews • Interviews • External project *(Rethink resources)* • Internal project *(T.Gottschalk)* • Testing of demagnetization methods

2.4 DATA COLLECTION METHODS

The project was positioned within the Division Quality Management and Environment, Health and Safety (QM&EHS) department in Vejle, Denmark, which held a governance position related to these aspects.

Throughout the duration of the project, most of the time was spent at the company, with regular visits to the university for occasional courses, conferences and workshops. Regarding data and information, the author was treated like a regular employee with full access to company information, including documents and access to relevant internal colleagues. This gave the possibility to interact and collaborate with colleagues from different of functions and levels in the organization. Being an 'insider', regularly interacting with other functions while also being confronted with 'real business problems' helped shape the understanding of the topic specific to Siemens' organizational context. Performing research within the company, gave a deep understanding of the topic and its contextual relationship – deeper than studying a case company from the 'outside'. (Karlsson, 2009) On the other hand, there were implications on the research and scope of the project as a result of the author's daily integration in the company. Firstly, remaining objective is a key attribute for any researcher, but especially those with strong connections to the studied object, such as in this project. Secondly, being an industrial PhD also implies 'carrying out a research project where results are applied in an enterprise setting. This means that the research is continuously shaped by the company's needs. Bryman (2015) acknowledges this changing focus when doing research in business settings and further points out the importance of a researcher to remain flexible in the scope of work. (Bryman, 2015) This was also the case in this project, where an initial project plan was developed before the start of the project, but was iterated and changed throughout the duration of the project e.g. giving more attention to recycling of blades and magnets due to the direct need in the company and less on e.g. business models. Overall, it can be stated that a mixed method approach was applied, where the studies had an interventionist ambition (Jönsson, 2010) in order to contribute to sustainable value creation.

2.4.1 DAILY WORK AND OBSERVATIONS IN THE COMPANY

Being close and within the company's daily on goings, is an integrated part of an industrial PhD project. In this project, the author could observe and experience the daily work directly influencing their research project – both in terms of understanding the contextual setting but also gaining insider knowledge and helping refine the research scope. Schultz and Hatch (2005) emphasize that a longitudinal relationship is key to experience at first-hand the dynamics embedded in practical settings, which enriches the relationship between researcher and practice. (Schultz & Hatch, 2005) Unstructured observations are what Bryman (2015) defines as a method to assess the practices and culture with the aim of developing a narrative of those practices. For this project, it means that meetings, workshop, conferences, trainings, meetings and even lunch talks were common modes of information collection internally in the organization. This means that this information was not systematically collected and stored, but still played a role in structuring the research. Yin (2003) notes that participant observations can strengthen the validity of the study. (Yin, 2003) Further, meeting records and email correspondence did also play a role as data input and these were able to be 'tracked' and reviewed for clarification purposes. Another interesting aspect was that the author had the opportunity to work as a production worker of wind turbine blades for a week to gain a better understanding of the structure of the blades and the methods in which they were produced. Throughout this time, there were many opportunities to discuss composite recycling possibilities with the production workers. Other examples included visiting operational wind power plants – both onshore and offshore as well as conducting internal workshops with service experts to assess the technical requirements for lifetime extension or remanufacturing of the existing fleet of installed wind turbines.

2.4.2 DOCUMENT ANALYSIS AND LITERATURE REVIEW

Document analysis and literature reviews were an ongoing method for data collection during the PhD project. The types of documents and literature reviewed were reflective of the case studied in this project.

Document reviews and analyses were often linked to company documents, which could be either in writing or of infographic character. They included company procedures, policies, memos, minutes of meetings, emails, presentations, reports and websites. These were used to understand, gain insights and analyze the selected case studies. Literature was reviewed to either perform extensive reviews of certain topics based on the specific cases or to guide and frame the project narrative. They also provided a theoretical background to support the analyses of the given cases.

2.4.3 INTERVIEWS

Qualitative interviews played a central role in some of the case studies. According to Brinkmann (2009) the qualitative interview seeks to understand the world from the perspective of the interviewees. In this way, it is a method to understand how the world looks from the interviewee, but the qualitative research interview is also a space for knowledge creation through the interaction between the interviewer and the interviewee. (Brinkmann, 2009) The knowledge created from the interview will have certain characteristics and will be constructed and relational which is based on conversation, linguistics, narratives and pragmatism. (Brinkmann, 2009)

Bryman (2012) divided the qualitative research interviews into unstructured or semi-structured. In an unstructured interview, the interviewer typically has areas of interest that are intended to be covered during the interview. Conversely, the interviewer has prepared a list of questions in a semi-structured interview but can vary how and when the questions are asked. Here, the interviewer can also ask supplementary questions.

Both unstructured and semi-structured interviews were used as data collection methods during this study. Unstructured interviews were mainly used when directing and guiding the research or seeking additional insights into a certain topic and often in more informal or virtual settings. They were also be used to identify potentials within a given topic. A sampling method, which Battaglia (2008) states that a non-probability form of sampling selects a representative sample based on an expert assessment of the respondents' abilities to provide comprehensive information, rather than basing it on statistical determinant. Semi-structured interviews were used when the research questions were already established. This lead to more in-depth and predefined questions in order to guide the interview sessions. This was often done in more formal settings – both in person and virtually. These were followed up by minutes of meetings to confirm the learnings. Respondents of the interviews were both internal and external stakeholders.

2.4.4 EXTERNAL INNOVATION PROJECTS

Two larger innovation projects with external participants played a central part in this PhD study. Those included GENVIND and Rethink Resources, which are described in greater detail below.

Both projects provided a basis to discuss the related topics with external experts, as well as feed the information back internally. This gave an opportunity to get insights into the topics that would be difficult to achieve without external consultation. Further, the established projects provided an opportunity to test ideas in practice. Finally, the projects brought together staff with different professional backgrounds, which created valuable inputs when positioning the problem fields in a circular economy.

2.4.4.1 GENVIND

GENVIND had the aim to identify and develop new and existing strategies with environmental and economic benefits for recycling composite material. This was piloted and demonstrated that the composite waste could find a secondary application in different products, components and construction applications. The project ran for four years (2012-2016) and had a wide range of participants from: 1) knowledge institutes and universities, 2) innovation networks and 3) companies both upstream and downstream in terms of their use of composites. The role of the author was project manager representing Siemens Wind Power in the innovation consortium.

2.4.4.2 Rethink Resources

Rethink Resources was driven by the following four organizations: the University of Southern Denmark (SDU), Danish Technological Institute (TI), Lifestyle and Design Cluster and CLEAN (Danish cleantech network organization). The project aim was to create a 'Center of Resource Efficiency', where the focus was to minimize resource losses in Danish companies through rethinking of product designs, optimization of production, improvement in exploitation production waste, increasing recycling as well as utilizing new business models. (Grüttner, et al., 2017) Further, the organization GS1 (international standardization company) participated and contributed in this project.

The main interlinkage with this PhD study were: 1) the use of experts for assessing potential recycling routes for NdFeB permanent magnets and 2) the use of experts handling data to support recycling e.g. through a 'product passport system'. The project was a two-year project (2014-2016) and the author's role was project manager representing Siemens Wind Power.

2.4.5 CONFERENCES AND WORKSHOPS

As a natural part of the PhD process, the author attended a range of conferences and workshops (see Table 2). This gave valuable knowledge – both directly and indirectly linked to the PhD project. The conferences and workshops were often planned around topics such as circular economy, renewable energy, life cycle management or alike, which expanded the general knowledge of these topics. Further, they provided inputs to research areas of relevance, research methods applicable and even direct knowledge that could directly be integrated into this PhD project. The workshops and conferences were also possibilities for disseminating preliminary findings of the PhD and discussing with a wider community of research peers, but also enabled the transformation of results for communication with non-scientific audiences. Further, feedback from a peer community supported the validation of the findings from the study – often through an iterative process.

Table 2: Overview of conferences and workshops attended during the PhD project.

Conference name (Place)	**Date**	**Dissemination type**
Fremtidens Energi (Aarhus, DK)	09.2014	Participant
ERECON Conference (Milano, IT)	10.2014	Participant
Circular Product Design (Delft, NL)	11.2014	Participant
Research seminar w/ Chalmers University (Aalborg, DK)	11.2014	Workshop
Hub North, Process Optimization in Wind (Aalborg, DK)	12.2014	Participant
Netværk for Bæredygtig Erhvervsudvikling, Circular Economy (Aalborg, DK)	03.2015	Workshop
Circular Economy Stakeholder Meeting (Copenhagen, DK)	04.2015	Workshop
Waste as a resource (Odense, DK)	04.2015	Participant
INNO-MT Yearly Conference (Lindø, DK)	04.2015	Participant
PLATE Conference (Nottingham, UK)	06.2015	Paper presented
DRIVE Conference (Rotterdam, NL)	10.2015	Participant
Global Cleaner Production and Sustainable Consumption Conference (Sitges, Spain)	11.2015	Two papers presented

2nd Prize Industrial PhD and Postdoc Association Communication Prize (Videnskab.dk)	04.2016	Published popular article
Product Passport (Høje Taastrup, DK)	08.2016	Presenter
Skab mere forretning med cirkulær økonomi (Odense, DK)	09.2016	Presenter
14th Global Conference on Sustainable Manufacturing	10.2016	Paper presentation
Globale Gymnasier (Vejle, DK)	11.2016	Presenter
Circular Economy - Lecture (AU Herning, DK)	11.2016	Presenter
Circular Economy Conference (Herning, DK)	11.2016	Participant
Siemens Innovation Days 2017 (Hamburg, DE)	03.2017	Presenter
LCA/Eco-design network (Vejle & Copenhagen, DK)	04.2017	Workshop
Circular Economy in the Wind Industry (Madrid, SP)	05.2017	Presenter
8th Life Cycle Management Conference (Luxembourg, LU)	09.2017	Poster presentation
18th European Roundtable of Sustainable Production and Consumption Conference (Skiathos, GR)	10.2017	Paper presentation
Grib verdensmålene (Copenhagen, DK)	11. 2017	Presenter

2.4.6 LIFE CYCLE ASSESSMENTS

Life cycle assessments were used as a quantitative method to evaluate different scenarios and products during the project. This included ‘Goal definition and scope’, ‘Data collection’, ‘Modelling and impact assessment in SimaPro software’, ‘Interpreting results’, ‘Preparing EPDs and communication material’, ‘Disseminating the results internally and externally’. More precisely, the role of the author was supporting for the first full scale LCAs in 2014 and communication and disseminating internally, whereas the author was the main responsible for modelling, data collection communicating and disseminating the LCAs of the internal projects as well as the full LCAs of the 7MW and the two 8MW turbines.

Methodological choices can be seen in the publications listed below in Table 3.

Table 3: Life cycle assessment activities during the PhD project.

Year	**Scope**	**Publications**	**My input**
2014	Full scale LCAs of all product platforms (G2, D3, G4 and D6)	(Siemens Wind Power, 2015; Bonou, et al., 2015; Bonou, et al., 2016; Bonou, 2016)	• (Data collection) • Preparing EPDs and communication material • Disseminating the results internally and externally
2015	LCA comparison of generator technologies	Internal assessment – briefing report	• All stages – from goal and scope to preparing and disseminating the results internally and externally
2017	Full scale LCA of D7 platform	(Siemens Gamesa Renewable Energy, 2017)	• All stages – from goal and scope to preparing and disseminating the results internally and externally
2017	Full scale LCA of D8 platform (154 meter rotor)	Internal project	• All stages – from goal and scope to preparing and disseminating the results internally and externally
2018	Full scale LCA of D8 platform (167 meter rotor)	(Siemens Gamesa Renewable Energy, 2018)	• All stages – from goal and scope to preparing and disseminating the results internally and externally

2.4.7 RELATED INTERNAL WORK

During the project period, the author also collaborated with a number of other academic projects related to Siemens Wind Power, which helped shape the understanding of this PhD project. This included two other industrial PhD projects, fours master projects and a bachelor project, which the author either participated in or gave input/supervision to (see Table 4).

Table 4: Overview of related bachelor, master and PhD projects supporting the PhD project.

Project title	**Student(s)**	**Submission year**	**University (Degree)**
Recovering critical materials in wind turbines	J.P. Jensen	2014	Aalborg University (M.Sc.)
Waste management of end-of-service turbines	R. Nommik S. Karavida	2015	Aalborg University (M.Sc.)
On the shoulders of giants – life cycle based eco-design applied in wind energy technologies	A. Bonou	2016	Danish Technological University (PhD)
Analyse und Bewertung der Kritikalität strategisher Rohstoffe in der Windindustrie	T. Gottschalk	2016	TU Berlin (B.Sc.)
Economic viability and environmental assessment of disposal methods for wind turbine blades	C. Gleitsmann	2016	Southern University of Denmark (M.Sc.)

B2B engagement for sustainable value creation	G. Jones S. Williams S. Burnette S. Levine	2016	Bard College (MBA)
Brokering eco-design practices	K. Skelton	2017	Aalborg University (PhD)

The first supporting project of the PhD project was the author's own thesis (Jensen (2014), for which the PhD project could be seen as a continuation. The project analyzed how SWP could apply circular economy thinking to the use of permanent magnets to increase the value of magnets at end-of-service life. This work was carried into the PhD work, where practical applications of the circular economy concept and related strategies were tested.

Nommik and Karavida's (2015) project analyzed the challenge of waste derived from wind turbines that have reached their end-of-service life. This thesis investigated the material composition of wind turbines and suggested comprehensive solutions, including concrete recycling guidelines, for addressing waste management. The project utilized the concepts of circular economy and industrial symbiosis to create two recycling guidelines for waste handling of the cables and electrical and electronic equipment included in the wind turbines. The author contributed as internal supervisor and provided input and reflections to the project.

Bonou's (2016) project was focusing on the application of LCA methodologies to assess the environmental impact of SWP's product platforms. The student conducted the full-scale LCA modelling and impact assessments of the G2, D3, G4 and D6 platform. The contribution by this project was mainly in the final phase of the LCA assessment, where results were interpreted, published in EPDs and presented internally to the SWP organization via smaller workshops.

Gottschalk's (2016) project analyzed and evaluated the criticality of strategic raw materials in the wind industry as part of a bachelor thesis. This included an analysis of the extent to which strategic raw materials in permanent magnets of wind turbines were a bottleneck factor. The role of the author in the project was supporting with internal knowledge regarding the topic.

Gleitsmann's (2016) project analyzed the economic viability and assessed the environmental impact of disposal methods for the blade components. This master's thesis was an ongoing project running in parallel with my participation in the GENVIND project. Like the former project, the role of the author was supporting with internal knowledge regarding the topic.

Skelton's (2017) project was ongoing during most of the PhD project. The project was greatly interlinked with the author's own project due to its topic and Skelton's role as company supervisor for the PhD project. Further, a group of Bard College, MBA students, who analyzed our customers' environmental and sustainability requirements, were co-supervised by the two authors. The learnings resulted in a poster for the LCM2017 conference and a journal manuscript. The work of Skelton was mainly related to eco-design and internal procedures whereas this PhD project focused more on circular economy and sustainable value creation.

2.5 VALIDITY AND RELIABILITY OF THE STUDY

Bryman (2012) states that validity can be referred to whether the aim is to identify, measure or observe. In qualitative research Bryman (2012) distinguishes between internal and external validity. Internal validity targets the agreement between the researchers' observations and the ideas that developed based on these observations. External validity refers to the generalizability of the findings to other social contexts. (Bryman, 2012)

During the project, validation of information either from literature and document review, observations or interviews were tried in best possible manner – what Bryman (2012) defines as respondent validation. (Bryman, 2012) This meant asking the producer of the written text, if my understanding of the topic was right, resending minutes of meetings and confirming interviews through follow up documentation.

As stated, Bryman (2012) refers to external validity as generalizability. Further, it is stated that in qualitative research it is difficult to generalize, when using case studies and small samples. (Bryman, 2012) However, Flyvbjerg (2006) argues that generalizability is possible, but this is dependent of the selection criteria. The cases studied in this project are different in nature and generalizability differs between cases. However, some findings can relate to Flyvbjerg's notion that critical cases 'permit logical deductions, such as if this is (not) valid for this case, then it applies to all (no) cases'. (Flyvbjerg, 2006) Generalizability of case studies is often limited however, the research framework and methodology can act as guideline to make comparable studies of e.g. other product groups or other settings. The generalizability of each of the case studies will be reflected on in chapter 12.

2.6 REFLECTIONS

The study used a mix of quantitative and qualitative methods. Life cycle assessments were the primary quantitative method used to assess the impact of a given product scenario. However, the majority of methods applied were qualitative, which is recognized for providing an in-depth understanding of a problem field. Circular economy as an umbrella concept was used for structuring the thesis and its broad definition is reflected in the different applications of each of the chapters/papers. This project has analyzed parts of the relationship between the wind energy sector and the circular economy and it provides a first attempt of guiding future analyses and offers a basis for future research related to circular economy and sustainable value creation in the wind industry. If the circular economy concept is intended to provide sustainable value creation, future research can include social impact assessment and business model considerations to a larger degree than this project has done.

Further, this research encompassed a pragmatic approach. A pragmatic epistemological approach was chosen due to its industrial character to be able to research business challenges and real life problems.

To address *the business potentials of narrowing, slowing and closing the loops* is a wicked problem and requires research into a complex system, which is constantly changing. It has been sought to analyze the cases applying systems thinking (Richmond, 1994), but even that requires setting boundaries, which are subject to expansion and contractions.

Further, the study was situated somewhere between the technical and social sciences. Two sciences with their own strong 'vocabularies', so much efforts were needed to be able to understand this. Combining these sciences was essential in 'circular economy' research and is considered in this study as crucial to deliver sustainable value creation.

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3. THE WIND INDUSTRY AND THE COMPANY

3.1 THE WIND INDUSTRY

In this chapter, an overview of the wind power industry, Siemens AG and Siemens Wind Power is provided.

The wind industry section emphasizes the industry's historical evolution from a grassroots movement to a modern industry of industrial scale. The global status of installed capacity, technological descriptions of components, materials and recent innovations, value chain characteristics and shifts amongst key players are provided and highlight the industry's growth and associated challenges. The section concludes by presenting the environmental and social aspects of wind power that are commonly referenced in the scientific literature.

The company section describes the company in which the PhD project took place and its role in the wind industry. Further, the links to the mother company, Siemens AG, its history and offerings in the wind market, environmental programs and practices is described to provide a basic understanding of the structure of the company.

3.1.1 WIND POWER AND THE WIND INDUSTRY EVOLUTION

Wind power is indirectly dependent on the suns energy. Winds occur as a result of the uneven heating of the atmosphere, variabilities of the earth's surface and its rotation. The kinetic energy in moving air (the wind) is converted into mechanical power, which can be used for specific tasks such as grinding grain, pumping water or generating electricity. Wind turbines are thus energy converters, and are today used mostly for the generation of electrical energy.

Wind is one of the oldest sources of energy and has been used for thousands of years in a wide range of applications (for historical overviews refer to e.g. (Gipe, 1995; Ackermann & Söder, 2002; Pasqualetti, et al., 2004; Musgrove, 2010; Kaldellis & Zafirakis, 2011; Maegaard, et al., 2013). The earliest-known vertical axis designs originated in Persia around 200 B.C. Later these ideas were brought to Europe and changed to a horizontal axis design and was mostly used for mechanical applications. Electrification made wind power considered a technology of the past and nearly forgotten. However, the oil crisis in the 1970s and the anti-nuclear movement in the 1980s caused the resurgence of wind technologies for electrification. Between 1973 and 1986 wind turbines changed from domestic and agricultural purposes (1 to 25 kW) to utility scaled machines (50 to 600 kW) (Kaldellis & Zafirakis, 2011). During the 1990s the turbines grew in size from kW to MW and in 1991 the first offshore wind farm was installed. Today, wind power is one of the fastest growing energy sources globally (Maegaard, et al., 2013; Wagner & Mathur, 2012)) with turbines in the 7-9MW class. Siemens Wind Power has indicated a 10MW+ turbine in coming years (Weston, 2016a).

The wind energy hosts a series of advantages, which contributes to the industry's growth rate. It is a renewable energy technology that does not rely on resources to fuel, it does not produce emissions during its operation stage or hazardous waste at its end of life. Further, it is a domestic source of energy for many regions and wind farms can be built with different capacities and installed in many location types. As other energy technologies, wind power is also facing some challenges. One of the key challenges that have gained a lot of attention in recent years is the levelized cost of energy (LCoE), which has been high compared to other conventional energy sources. The wind industry has been working towards a levelized cost of energy that is competitive with the ones of conventional energy sources (Wiser, et al., 2011; European Commission - Joint Research Center, 2011).

3.1.2 GLOBAL STATUS

The global wind power capacity has dramatically increased in the last decade, nearly eight-fold. This increase is shown in Figure 2 as the annual installed wind capacity and in Figure 3 as the accumulated installed capacity. The wind power industry experienced a record year in 2016 where annual installations surpassed 63 GW for the first time. (GWEC, 2016a) and increasing the investments in wind energy also. The electricity from wind turbines made up around 4% of the electricity demand worldwide in 2014 (IEA, 2016; GWEC, 2016a). Onshore wind turbines have been the most widely technology utilised but with large increases in offshore wind in recent years (GWEC, 2016a).

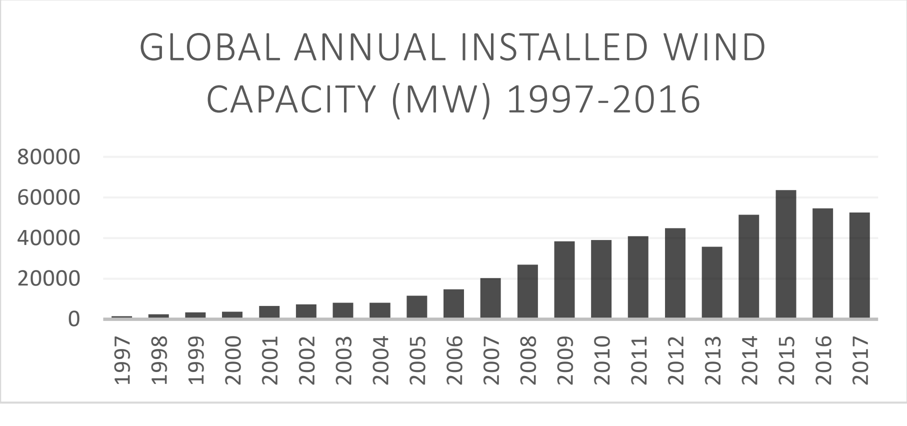

Figure 2: Global annual installed wind capacity in MW (1997 to 2016) (own illustration based on GWEC, 2017)

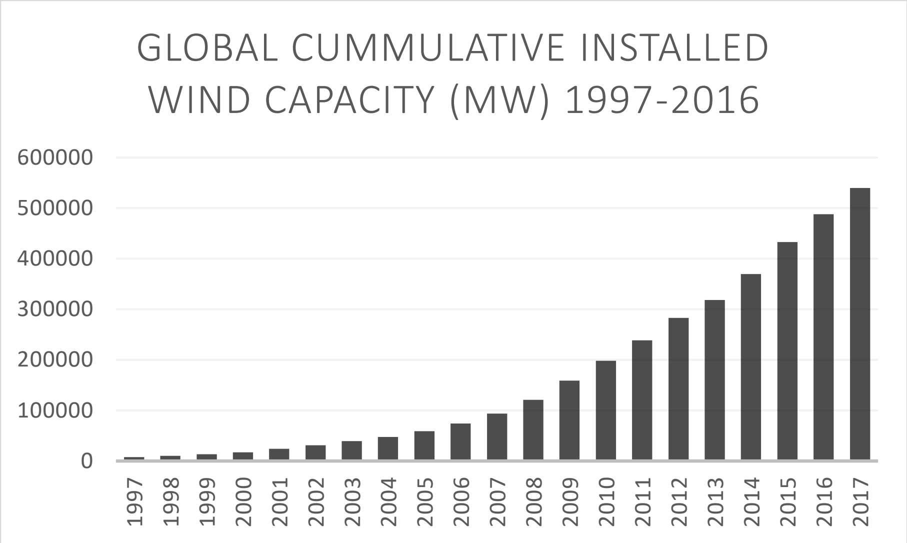

Figure 3: Global cumulative installed wind capacity in MW (1997 to 2016) (own illustration based on GWEC, 2017)

More than 90 countries have commercial wind power installations with Asia, USA and Europe as the leading regions in terms of installed capacity. Approximately, half of the total annual installed capacity is in China, whereas the offshore industry mainly is in Europe. Forecasts indicate a steady growth in the future for emerging countries such as Latin America, Africa and Middle East (GWEC, 2016a). The theoretical potential for wind is estimated at 1,700,000 TWh/yr (Rogner, et al., 2000), which is way above the World's current energy demand. However, factors such as geography, technology economy and market conditions affect the realistic potential. (Wiser, et al., 2011) concludes that economical and institutional factors will be the largest constraint and that the technical potential is in the range of 23,400 to 162,000 TWh/year. As the technology develops, cost decreases and more policy measures and market incentives are introduced the technical potentials will increase. (Krewitt, et al., 2009) A range of scenarios have been developed to estimate the growth of the wind power industry all concluding that wind power will be central in the future energy scenarios with promising growth rates (GWEC, 2016b) .

3.1.3 TECHNOLOGY AND VALUE CHAIN

Wind turbines have, as mentioned, evolved from small scale, simple devices to industrial scale, sophisticated machines. Advancements have been realized in diagnostic control systems, design standards, manufacturing, operation and maintenance procedures. More than three decades of basic and applied research, ongoing cost reductions and government policies to expand the share of renewable energy have contributed to the industry's rapid development.

Basic design principles: Wind turbines typically start rotating, and thereby generating electrical power, at wind speeds of three to four m/s (cut-in speed). Most turbines stop extracting energy at speeds of 20-25 m/s (cut out speed) in order to prevent damage to the turbine's structural components (Wiser, et al., 2011). Higher energy capture can be achieved through different design configurations such as higher wind speeds, higher generator capacity, longer rotor diameters, aerodynamic add-ons, taller towers, etc.

Turbine components and materials: Wind turbine configurations can differ significantly i.e. horizontal or vertical axis designs, rotor blades positioned upwind or downwind of the tower. Commercially available turbines have a horizontal axis design, where three blades are positioned upwind. A wind turbine can have upwards of 8,000 components (EWEA, 2009a).

Table 5: Description of wind turbine components (based on (Janssen, et al., 2012; Aubrey, 2007; Gasch & Twele, 2012))

Rotor	Consists of the rotor blades, aerodynamic break, hub and spinner and represents the heart of the turbine. The *rotor blades* are considered a critical component by manufacturers because they capture kinetic energy from the wind. They are made from fiber-reinforced plastics and new blades range in size from 30 to 80 m. Three blades are conventional but two bladed turbines also exist.
Drive train	Consists of the gearbox, generator, rotor shaft, bearings and brake. The power from the rotation of the wind turbine rotor is transferred to the generator through the drive train, i.e. through the main shaft, the gearbox and the high speed shaft. These components transform the variable low speed rotational energy to higher speeds, needed for the generator. Iron and steel are the predominant materials. Some gearboxes have been replaced by direct drive mechanisms that improve efficiency and decrease maintenance costs. The *generator* converts mechanical energy into electrical energy. Most generators are made of steel and copper. Permanent magnets are used if there is a direct drive mechanism instead of a gearbox. Permanent magnets contains rare earth elements such as neodymium and dysprosium. *Bearings* are considered the Achilles heel of a wind turbine because they allow the components to smoothly operate. They are

	made of high strength steel and have bore diameters of between 100 and 700 mm. The *shaft* transmits rotational forces from the blades to the generator. The shaft is made of steel or iron. The *nacelle* is a lightweight fiberglass structure that contains most of the mechanical and electrical components and protects them from the external environment. Some are large enough to host a helicopter pad for technicians.
Supporting structure	Consists of the tower and foundation. The *tower* supports the nacelle. Towers are usually tubular in shape and made of steel but concrete and lattice structures are also commonly used. They can have heights of 160 m and normally account for 30 to 65% of the turbines overall weight. The *foundation* is a concrete base that is reinforced with steel bars to which the wind turbine is affixed.
Control system	Consists of electrical components that are used for the control and grid connection. The control system includes yaw, pitch, speed, and brake systems. These parts manage blade and turbine direction and speed to ensure optimal energy output and correct supply to the grid. *Power converters* transform the direct current from the generator to an alternating current for the power grid. Power converters are electronic devices composed of semiconducting elements.

Turbine size, capacity and lifetime: The wind turbine size has significantly increased in the last three decades (see Figure 4). Since the 1980s, wind turbine capacities have increased from 75 kW to 5 MW for onshore and from 3 to 9 MW and larger for offshore, where rotors are currently exceeding 164 m diameters and towers are surpassing 150 meter heights (GWEC, 2016b). The trend is that the installed turbines are getting larger both onshore and offshore. (Navigant Research, 2015). Commercial wind turbines are type-certified to safely withstand harsh environments for 20 years onshore, although they may last longer if installed in low turbulence regions. Since conditions at sea are less turbulent than on land, offshore turbines are type certified to last 25 to 30 years (EWEA, 2009a).

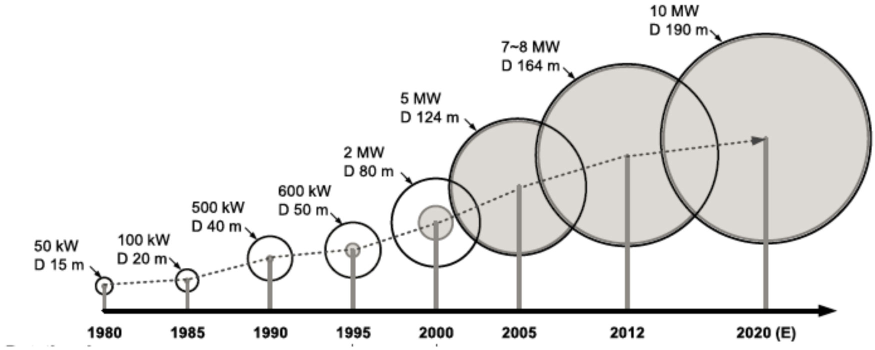

Figure 4: Development in size of wind turbines between 1980 and 2020. D means diameter of the rotor. (Blaabjerg & Ma, 2017)

Costs: LCoE have been the main competition parameter for wind against conventional energy sources the last years. In regions with good resources wind are cost competitive with other energy sources (IEA, 2010). The prices of onshore wind power have been in the range of 43 to 182 USD per MWh and 136 to 275 USD per MWh, which shows the variation throughout different locations (IEA, 2015). The wind industry is focusing on improvements in the full life cycle to lower the costs with both incremental potentials as well as radical innovations such as as floating turbines; higher altitude wind power machines; grid integration and electricity storage (Wiser, et al., 2011) . Capital costs account for 65 to 85% of the total expenditure for onshore and 30 to 50% for offshore (EWEA, 2009a; IRENA, 2012).

Value chain: At the end of 2013 the industry employed roughly 600,000 people and is expected to employ upwards of 2,200,000 million by 2030 (GWEC, 2016b). Previously, a few major players dominated the industry but today it is composed of a network of diverse stakeholders that interact at all stages of a wind farms life cycle including suppliers, manufacturers, developers, owners, operators, etc. There are also a number of wind power consulting, research and certification organizations that assist at different stages of a wind power plants development.

There is a range of turbine manufacturers that dominate the industry with companies like Vestas, Siemens Gamesa Renewable Energy, Enercon (all EU), Goldwind, Sinovel (China) and General Electric (US) as the major ones, but also a large group of smaller manufacturers. Only a few – Vestas, Siemens Gamesa Renewable Energy, General Electric and Senvion – have entered the offshore market.

3.1.4 WIND POWER AND ITS ENVIRONMENTAL AND SOCIAL ASPECTS

There are a number of environmental and social aspects of wind power that can be considered as either beneficial or disadvantageous. Estimating these benefits and impacts can be difficult, especially when considering a life cycle perspective or comparing them against other energy sources. Evaluations are highly dependent on the assumptions that are made (system boundaries).

Benefits: (GWEC, 2016a) sees wind power as an important solution to climate change, energy security and price stability and credits the industry as a driver of new industries and employment. Benefits of wind power include, but are not limited to:

Displacement of fossil fuels: Wind power boasts a number of environmental benefits, but the most obvious relates to the displacement of fossil based power, and thereby greenhouse gases and other emissions during operation. Furthermore, the operational stage does not require fuel, which is typically obtained through intensive mining or drilling methods (e.g. coal or uranium) and avoids the production of waste by products (e.g. oil sands tailings ponds or radioactive waste). (GWEC, 2016b) estimates average carbon savings of 600 gCO2/kWh by using wind compared to fossils.

Low carbon footprint: Life cycle assessments (LCAs) according to ISO 14040 and 14044 standards are commonly used to evaluate the positive and negative contributions from a turbine/wind farm across its life cycle stages. They provide a comprehensible and consist way to evaluate the impacts at different life cycle stages of a wind farm e.g. material extraction, manufacturing, construction, assembly and installation, operation and service, end of service and dismantling (EWEA, 2009b). Some have been peer reviewed and scientifically published (Ardente, et al., 2008; Haapala & Prempreeda, 2014; Garrett & Rønde, 2013; Guezuraga, et al., 2012; Martínez, et al., 2009; Raadal, et al., 2014; Schleisner, 2000; Wagner & Mathur, 2013; Weinzettel, et al., 2009), while others have been performed by manufacturers or developers (Gamesa, 2013; Gamesa, 2014; Siemens Wind Power, 2014a; Siemens Wind Power, 2017a; Vattenfall, 2014; Vattenfall, 2016; Vestas, 2006; Vestas, 2011a; Vestas, 2011b; Vestas, 2014). The aspects can be assessed based on a number of impact categories (e.g. climate change, resource use, land use, toxicity, etc.) but most wind related LCAs use climate change in terms of CO2 equivalents per unit (1 kWh) electricity generated which enables a comparison between other energy sources. The majority of greenhouse gas estimates range between three and 20 grams CO2 eq. per kWh, but older studies also show higher values up to 45 CO_2 eq. per kWh (Wiser, et al., 2011; Dolan & Heath, 2012).

Short energy payback: The energy payback time is the common reference used for wind farms, representing the operational time needed to produce the equivalent amount of energy that is required to pay off the wind farms life cycle impacts (e.g. manufacturing, installation, servicing and decommissioning). (Wiser, et al., 2011) reviewed 20 studies and found that the median energy payback time was 5.4 months. Different turbine designs and assumptions made explains variability in the results.

Water preservation and conservation: (OECD, 2013) informs that future climate change and population growth will intensify water scarcity and that by 2050, 40% of the world's population will encounter some form of water stress. Conventional power plants (e.g. thermal and nuclear) require high amounts of water for cooling purposes, and represent the largest consumer of water in the EU (44%). In contrast, wind power essentially utilizes no water thereby contributing to its conservation and preservation (EWEA, 2014c).

Net social benefits: Environmental LCAs and life cycle costing methods have become well established in both academia and industry. More recently, social LCAs (S-LCAs) have been introduced which add an extra dimension to the impact analysis domain and provide valuable information for companies who seek to produce or purchase responsibly. S-LCAs determine potential social and socio-economic aspects of a product's value chain including the benefits and impacts to the workers, value chain actors, local communities, consumers and broader society. The net benefits of wind power tend to be underestimated by not including impacts such as those included in S-LCAs or related methodologies.

There has been a lot of social research on wind power (i.e. employment benefits, stakeholder engagement, local nuisance impacts like visual impacts, noise, etc.) to date but only three studies have applied the S-LCA or similar methodologies to wind power specifically. Vattenfall (has included a S-LCA as an appendix to its EPD for electricity from their Nordic wind farms based on the Guidelines for Social Life Cycle Assessment of Products (UNEP/SETAC, 2009) and the Handbook for Product Social Impact Assessment (Roundtable for Product Social Metrics, 2014). Similarly, Scottish and Southern Energy (SSE) measured the social and economic implications of the extension to the Clyde wind farm using the Total Impact Measurement and Management methodology. Including socio-economic measures in the cost of energy has been proposed by Siemens Wind Power to reflect the complete cost-benefit ratio of the various energy technologies. (Siemens AG, 2015). Society's Cost of Electricity (SCOE) is an alternative evaluation model, which includes factors such as subsidies, employment effects, transmission costs, social effects, variability costs, geopolitical risk and environmental impacts. This assessment has shown to in favour of the renewable energy sources compared to fossil fuels.

Disadvantages

Wind power has been associated with some potential environmental and social impacts. A number of authors provide a full picture overview of these impacts including (Dai, et al., 2015; EWEA, 2009b; Saidur, et al., 2011). Topical areas of interest include, but are not limited to:

Wind variability: The variability of wind affects the operation, and thereby emissions, of conventional based energy sources. The fluctuations in wind power generation causes part-loading of fossil based energy sources which reduces the power plants efficiency compared to a full-loading plant. An impact LCAs seldom account for.

Impacts to flora and fauna: Siting a wind farm has impacts on the area of construction. Broader planning and siting requirements i.e. environmental impact assessments, have improved because of these concerns.

Some of the most publicized concerns among communities are collisions with birds and bats and the impacts to benthic zones and fisheries. Wind turbines can kill birds and bats and negatively affect marine life. Impacts will vary based on regional characteristics, migration periods and wind farm characteristics.

A study by (NRC, 2007) found that bird mortality rates ranged between 0.95 and 11.67 deaths annually per MW. Comparatively, bat mortality rates ranged between 0.8 and 41.1. Siting wind farms away from high bird and bat population densities and altering turbine operations under certain conditions are two prospective mitigations (Baerwald, et al., 2009; Arnett, et al., 2011), which is also integrated in some turbines today with e.g. Bat-systems that can shut down the operation of the turbine if bats are detected. However, when put in the context of other fatalities caused by anthropogenic causes e.g. buildings, windows, vehicles, other energy sources etc., the estimated cumulative impact on birds and bats is minimal (Wiser, et al., 2011; National Wind, 2010).

Empirical research on offshore impacts is also not as extensive compared to onshore and has so far, mainly been conducted in northern European (Leonhard, et al., 2011; Lindeboom, et al., 2011; Mann & Teilmann, 2013). A study by (Bergström, et al., 2014) indicates some disturbances i.e. noise and vibration, during the installation and decommission stages due to drilling and dredging activities on the sea floor. They indicate that fish and marine mammals return soon after activities cease. During the operative stage, habitat gain typically increases species populations, which can have both positive and negative effects. Support structures create an artificial reef effect, which has been used to improve biodiversity (Mikkelsen, et al., 2013), tourism (Wilhelmsson, et al., 1998) or fisheries (Seaman, 2007). However, the offshore support structures can also introduce non-indigenous species (Bulleri & Airoldi, 2005). Increases in vessel traffic during installation and service stages can also contribute to noise and the introduction of invasive species. In order to minimize these impacts, ecological reports are needed, prior to offshore installation and commissioning (Mangi & Mangi, 2013). Recently, Slavik et al (2017) concludes that offshore wind farms act as marine preservation areas, because fishing and bottom trawling is not allowed for safety reasons. These areas can support greater biodiversity than unprotected areas. However, it is also stated that long-term effects are yet not known (Slavik, et al., 2017).

Socio-environmental impacts: There are also a number of socio-environmental impacts, which are commonly referred to as nuisances, e.g. impacts on proximate communities, aviation, shipping and communication. Wind farms encompass large land areas (5 to 10 MW per km2) that could be used for other purposes (Wiser, et al., 2011). Further, individual turbines and wind farm sizes are growing in scale and are commonly sited at higher elevations. Visual impacts are thus one commonly referenced concern among communities (Ledec, et al., 2011). This aspect has resultantly been included as a point in siting procedures, requiring photos and the implications on property value to be noted. Noise and shadow flicker are other concerns frequently raised. Standards and regional legislation have been introduced to indicate permissible acoustic levels while control systems and different tip shapes have been designed to reduce shadow and noise effects. Despite these concerns, a number of studies find that the general public accepts wind power (Klick, 2010; Poumadére, et al., 2011; Warren, et al., 2005). Addressing these concerns early in the siting and planning phases through participatory and transparent methods is of utmost importance to a wind projects success (Gross, 2007; McLaren Loring, 2007; Wolsink, 2007). Other studies have indicated that local ownership and other benefit sharing arrangements improve the social acceptability of wind projects and speed up the planning process (Cowell, et al., 2011; Gross, 2007; Ledec, et al., 2011; Wolsink, 2007).

As described, the wind industry has experienced a significant increase in installed capacity, turbine size in recent year. The industry has moved from small utility-scale application to a highly industrialized industry, where consolidation is taking place in the value chain. The wind power industry is born out of the idea of low-carbon technologies for energy production, but are also facing challenges related to cost of energy as well as social acceptance.

3.2 THE COMPANY

3.2.1 ORGANIZATIONAL HISTORY AND STRUCTURE

This section briefly describes the organizational history and structure of both Siemens' and the Wind Power Division. The reasoning for including Siemens AG is the close interlinks that were present – especially in the beginning of this PhD project, which have direct impacts on the environmental practices established in Siemens Wind Power. The vision and mission of both are also explained as well as the key focal areas, ingenuity for life and must win battles in Siemens AG and SWP respectively.

3.2.1.1 Siemens AG

Siemens AG is a multinational conglomerate with headquarters in Berlin and Munich. It was founded in 1847 by two men as the "Telegraphen-Bauanstalt von Siemens & Halske" company. Today it is one of the largest technology companies focusing on electrification, automation and digitalization (Siemens, 2017a). Siemens AG frames itself in the following way:

> *"For over 165 years, Siemens has stood for engineering excellence and innovation, for quality and reliability, for human creativity and drive, for stability and financial solidity and, last but not least, for good corporate citizenship" (Siemens, 2015)*

End fiscal year 2016, the company employed 351,000 employees globally in over 200 countries. At the same time, it generated revenues from continuing operations of €79.6 billion and a net income of €5.6 billion. SWP accounted for 7% of the SAG revenue (Siemens, 2017b).

As shown in Figure 5, Siemens AG consisted of ten divisions, of which SWP was one of them as of 2016. The divisions are shown in relation to the portfolio and megatrends. The managing board and corporate functions are depicted also in relation to the divisions. Today, SWP and Healthineers are separately managed.

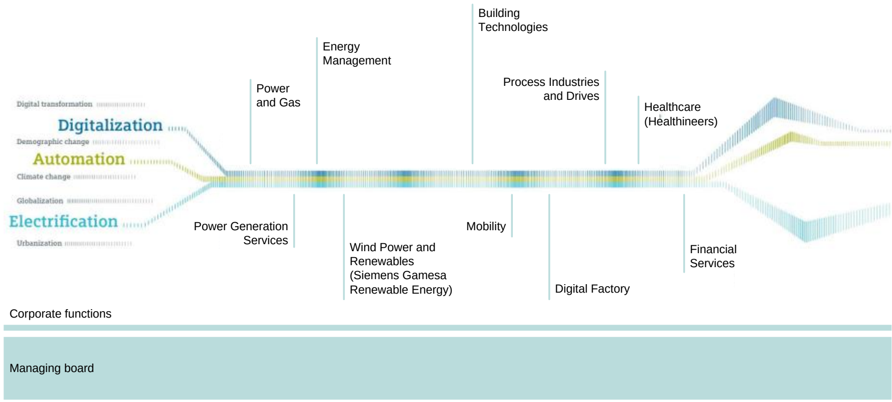

Figure 5. Organizational structure in Siemens as of 2016 including divisions along portfolio (Siemens, 2017c)

Vision and mission: In 2014, the company launched a five year company-wide strategy (Vision 2020) that is based on three core elements:

Siemens' mission, or what it calls "path" to self-understanding and how it defines its aspirations:

> *"We make real what matters, by setting the benchmark in the way we electrify, automate and digitalize the world around us. Ingenuity drives us and what we create is yours. Together we deliver"*

A consistent strategy with seven goals and a positioning within electrification, automation and digitalization which are based on long term trends that define the company's markets and stakeholder requirements:

> *"Vision 2020 defines a concept that will enable us to consistently occupy attractive growth fields, sustainably strengthen our core business and outpace our competitors in efficiency and performance" (Siemens, 2014)*

In 2015, Siemens launched a new brand "Ingenuity for Life" out of response to both the new Siemens strategy (Vision 2020) and the 200th birthday of its founder Werner von Siemens. Further, Siemens AG CEO, Joe Kaeser was cited:

> *"For me, "Ingenuity for Life" means that we will always place our innovative strength at the service of society. And we intend to live up to this aspiration, today and in the future" (Siemens, 2016).*

This reframing and the close links to global megatrends shows the commitment to center its business around societal issues and adding value by doing so. Siemens Wind Power plays a vital role in the providing clean energy to an electrified society.

3.2.1.2 Siemens Wind Power / Siemens Gamesa Renewable Energy

The history of SWP dates back to 1980, with the foundation of Danregn and progresses through the acquisition by Siemens in 2004, to today's situation of the merge with Gamesa Technology Corporation. Below I describe the technological developments, key milestones and the expansion of the company that are summarized in Figure 6.

Figure 6: Time line of the development of Siemens Wind Power/Siemens Gamesa Renewable Energy (Own illustration)

In **1980,** the Danish company Danregn, known for its irrigation systems, began developing wind turbines based on a new market demand in response of the 1970s international energy crisis. Danregn Vindkraft's first wind turbines had generator powers of 20 to 30 kW, rotor diameters of 10 meters and tower heights of 18 meters. The company changed its name in **1983** to BONUS Energy due to the fact that Danregn could not be pronounced in English (Maegaard, et al., 2016). In **1982**, they delivered their first six turbines to Oak Creek in Tehachapi, California. **1991** marked an important milestone for us with the creation of the world's first offshore wind farm, featuring 11 units of the 450 kW BONUS turbines, Vindeby. The original turbines with a total capacity of 4.95 MW were decommissioned in 2017 (Lehn-Christiansen, 2017)**.**

Continuing the development of its product portfolio, BONUS Energy managed to break the 1 MW mark in **1997** and the 2 MW in **1998**. Twenty 2-MW turbines were installed in the Middelgrunden Offshore Wind Farm, close to Copenhagen in **2001** (ENS, 2017) and the number of employees had increased from 350 to 400 (Maegaard, et al., 2016). Prior to **2002**, all major components were sub-contracted until BONUS Energy launched its own blade factory in Aalborg (Ing, 2002). In **2004**, Siemens took over BONUS Energy as its first time entrance into the wind energy business (Siemens, 2004). After the acquisition, SWP grew rapidly. Between **2004** and **2011**, employee numbers grew from 800 to 7,800, of which 5,200 were in Denmark and 1,000 in Germany. A number of regional sales and project management offices as well as production facilities were established globally. In **2009**, SWP experienced a number of highlights: a new turbine design using direct drive and permanent magnets began replacing geared turbines (Buck, 2013). The company also expanded its cooperation with DONG Energy by entering an agreement to deliver up to 500 offshore turbines with a total capacity of 1,800 MW (Siemens, 2009a) and with Statoil Hydro by installing the world's first large scale floating wind turbine at Hywind where it was tested and agreed the park would be expanded (Siemens, 2009b).

In **2010,** SWP acquired 49% of A2SEA, an offshore wind farm installation company (Siemens, 2010) which it later sold in 2017. Siemens´ goal with its commitment in A2SEA was to advance the industrialization of offshore wind power. The same year, it was announced SWP would become one of nine divisions within Siemens and the headquarters were relocated from Brande, Denmark to Hamburg, Germany. The company also expanded its operations by establishing a service business unit to handle the growth in maintenance and upgrade services. SWP introduced a redesigned blade, the quantum blade, in **2011** with revised root and tip sections and a lighter design than its previous versions, which reduced noise levels (Siemens, 2017e). The first 6 MW offshore prototype was also installed at the test site at Hoevsoere, Denmark which included a 75 meter blade (Siemens, 2011). On May 12th **2012**, Siemens' SWT-6.0-120 offshore wind turbine prototype produced 144,000 kWh of electricity representing a new record for wind turbines in Denmark within a 24-hour period, and equivalent to the electricity consumption of approximately 10,000 households in the same period (Siemens, 2012a).

Another milestone was the **2013** inauguration of the world's largest offshore wind farm, London Array, with a combined capacity of 630 MW. It set a world record in **2015** by generating 369 GWh during the month of December (Weston, 2016b). In **2014,** SWP continued its path of establishing itself as one of the largest companies in the wind energy industry. According to MAKE and BTM, Siemens Wind Power ranked 1st and 2nd respectively (Windpowermonthly, 2015; Rechargenews, 2015). It was also the year, where EPDs for the entire product portfolio were published (Siemens Wind Power, 2014a). Installation of a 7 MW prototype at Oesterild Test Center occurred in **2015**, which was an upgrade of the 6 MW platform including upgraded magnets in the generator (Siemens, 2015). The 7 MW turbine was ranked as the world's best offshore turbine by Wind Power Monthly (de Vries, 2015a) and the 3MW DD as the best in its category this same year (de Vries, 2015b). An 8 MW was also announced for production. **2017** marked the end of SWP as the company was carved out of Siemens and merged with Gamesa Technology Corporate to form a "leader in the renewable energy industry" and "a big four of OEMs" with a combined installed capacity of 75 GW, installations in 90+ countries, 27,000 employees and an order backlog of €21 billion (Weston, 2017; Siemens Gamesa Renewable Energy, 2017). A few months into the merger, the new SG 8.0-167 DD turbine was announced – the 8MW wit 81,5 meter blades – and was quickly announced for a series of projects including the World's largest (at this moment), the Hornsea II project of 1386 MW. (Borsen, 2018)

Overall, SWP has undergone several organizational changes during the duration of this research, mainly due to its rapid organizational growth, which can be related to the industry's growth. These changes have had significant effects on the organizational structure as well as the products and policies as well as its environmental and product development practices. Figures 7 and 8 below illustrate this development, both in terms of increasing product size and installed MW per year.

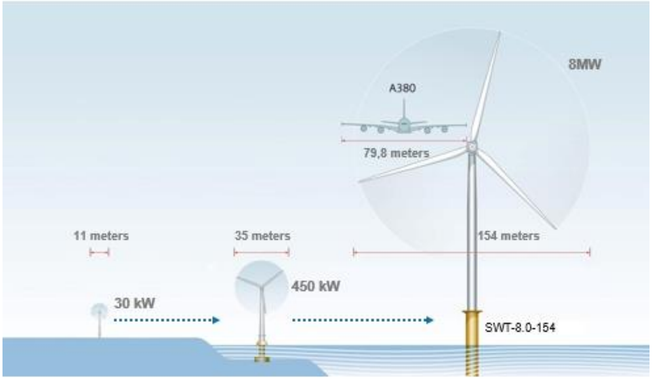

Figure 7: From 30kW wind turbines in 1980 to 8MW wind turbines in 2017 (Source: Siemens, 2016)

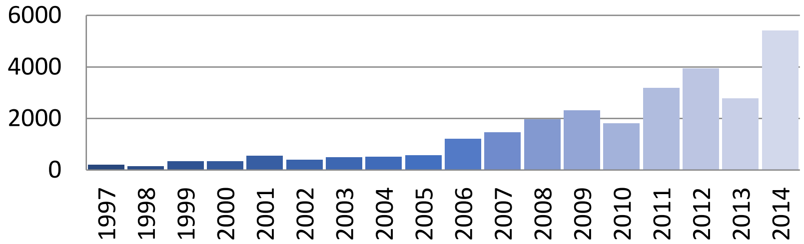

Figure 8: Siemens Wind Power installed capacity in MW from 1997 to 2014 (Siemens internal, 2015)

SWP is a matrix organization divided into the three market units: onshore, offshore and service. The market units are then supported by a range of division functions including EHS, where the PhD project is situated. In 2016, Siemens had approximately 12,800 employees, and an installed base of over 16,800 turbines in 40 countries with approximately 32,400 MW of capacity. In 2015 alone, the SWP installed almost 2,000 turbines accounting for roughly 5.6 GW of capacity (Siemens Wind Power, 2016a).

3.2.2 PRODUCT DEVELOPMENT PRACTICES

This section briefly describes the product development practices of both Siemens' and the Wind Power Division. The product and service portfolios of both are also explained as well as the key themes of environmental product portfolio and the product development process in Siemens AG and SWP respectively.

3.2.2.1 Siemens AG

Some of the key product innovations over Siemens' 168 years of operation can be seen in Figure 9. As shown, the company has continually adjusted its product portfolio e.g. the pointer telegraph (1847), the world's first locomotive (1879), the world's first electric streetcar (1881) are some examples from a long list (Siemens, 2017a). Today, Siemens' product portfolio and innovations reflect a number of megatrends spanning from digitalization, demographic change, climate change, urbanization and globalization. The company further positions its portfolio around three key areas: electrification, automation and digitalization.

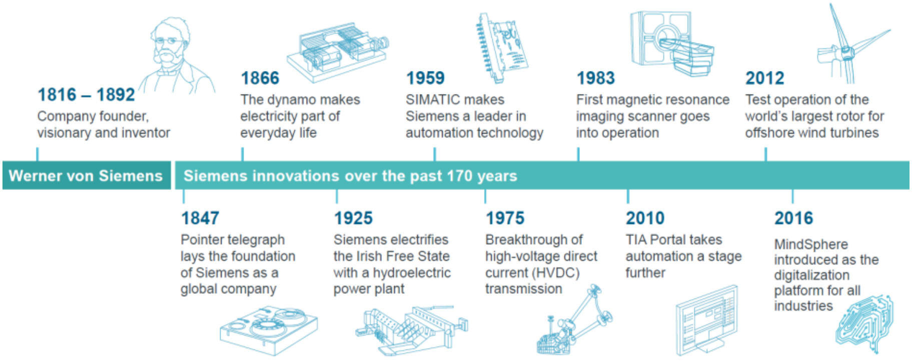

Figure 9: Siemens AG key product innovations (Siemens, 2017c)

Environmental portfolio: Through its portfolio of products and services, Siemens claims to embrace the technological shifts needed to address megatrends such as climate change and resource scarcity. In 2008, Siemens launched its first Environmental Portfolio which consisted of a bundled set of products and solutions that directly contribute to energy efficiency and renewable energies as a testament to this claim. The company has the goal its brand is globally recognized for sustainable, forward-looking technologies that can change the world for the better (Siemens, 2012b). Products must qualify for the portfolio by meeting clear criteria, which are based on life cycle assessments among other parameters. This includes newly developed products, components or services as well as existing ones that have been improved. Siemens product portfolio consists of mostly investment goods which last many decades, so energy and resource efficiency during the use phase is one of the main levers for supporting Siemens' customers in reducing their operational as well as total cost of ownership (Pfitzner & Lutz, 2015). Further, the Environmental Portfolio revenue in 2016 amounted to €36.3 billion, or 46% of Siemens' revenue from continuing operations (Siemens, 2017g). Products significantly contributing to the portfolio include combined cycle power plants, power plant modernization and upgrade activities, frequency converters and high-voltage direct current power transmission systems as well as power generation from wind turbines.

3.2.2.2 Siemens Wind Power

SWP operates worldwide to produce and to install wind turbines and to provide global service operations to installed turbines. The current portfolio includes four platforms and multiple product variations as shown in Figure 10 as of 2016. SWP has categorized its products into product platforms, which allows for standardized modules such as rotors, generators, towers and hubs to be used in the various wind turbines. They can be adapted to the site conditions and the requirements of the customer. Conditions can range from high wind to low wind areas, noise restricted areas, or locations with severe weather patterns. The service offerings both in combination with turbine sales and as a stand-alone concept are shown below. These range from basic scheduled visits (SWPS-100B) to complex service programs including remote diagnostic services, performance warranties and logistic solutions.

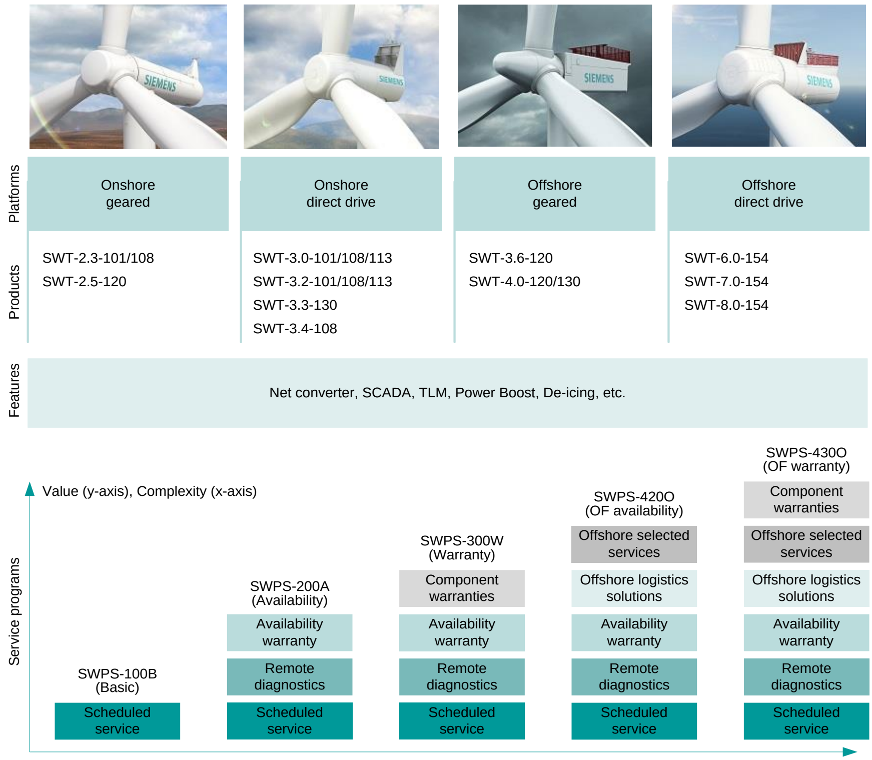

Figure 10: Overview of the platforms, products and service offerings as of 2016 (Siemens, 2016)

Social cost of energy: In 2014, the concept of a society's cost of electricity (SCoE) emerged at SWP. It is an alternative evaluation model from the LCoE debate, and expands to include additional costs borne by society such as subsidies, employment effects, transmission costs, social effects, variability costs, geopolitical risks and environmental impacts. Take for example the geopolitical risks that are not factored into the LCoE for fossil or nuclear power sources. When social values are factored into the cost of wind power comparatively with other technologies, the positive aspects related to increasing the deployment of renewables such as wind are strongly emphasized (Siemens Wind Power, 2014b; Siemens Wind Power, 2017b).

3.2.3 ENVIRONMENTAL PRACTICES

This section briefly describes the environmental practices of both Siemens' and the Wind Power Division. The EHS policy framework and scope of environmental activities of both organizations are explained as well as the key themes of Siemens' environmental product portfolio, climate neutral and business to society programs and the wind power division's EHS strategy and product related environmental activities.

3.2.3.1 Siemens AG

EHS and Sustainability topics have a central position in Siemens and are an integrated part of Siemens' strategy. In an interview about this year's UN World Environment Day theme "connecting people with nature", Klaus Luetzenkirchen, head of the Corporate Environmental Protection Department, is quoted saying:

> *"It is especially important for large and globally operating company such as Siemens to be a role model. It is up to us to set an example, because we have a great responsibility to our employees and the locations where we are active. This year's motto is a good opportunity to get back to nature! Because it is our most valuable asset. Nature gives us the resources needed for our products, moreover an intact environment is essential for the health of our employees"* (Luetzenkirchen, 2017)

This is supported by a number of internal guidelines that establish clear rules such as business conduct guidelines, code of ethics, principles of diversity, EHS policy, supplier code of conduct (Siemens, 2017f).

From a Siemens AG perspective, the environmental topics are split between two units; Corporate EHS and Corporate Sustainability, which briefly will be differentiated between below.

Corporate EHS oversees the EHS management system including uniform policies, standards and programs, companywide targets and internal reporting. Their primary focus is to improve EHS operations related to for example, manufacturing facilities, project sites, service operations and product related aspects.

To provide corporate governance on different operational EHS topics, Corporate EHS is divided into four groups and four corresponding EHS programs (see Table 6): "Serve the Environment" for industrial environmental protection, "Product Eco Excellence" for product related environmental protection, "Zero Harm Culture@Siemens" for safety and "Healthy@Siemens" for health management. The programs have their own resources allocated including a number of tools, guidelines and expert groups phrased as Centers of Competences, where best practices etc. are shared.

Table 6: EHS programs and related topic areas

Programme	**Serve the Environment**	**Product Eco Excellence**	**Healthy@Siemens**	**Zero Harm Culture@Siemens**
Group	Industrial environmental protection	Product related environmental protection	Safety	Health management
Topics	• Energy and climate • Waste management • Emissions • Water and soil protection • Biodiversity and nature preservation	• Substances • Critical materials • Product design • Life Cycle Assessment • Environmental product declarations	• Occupational health and safety • EHS emergency management • Fire safety and explosion prevention • Transport of dangerous goods • Radiation safety	• Healthy work environment • Pscychological well being • Physical activity • Nutrition • Medical care

The work done with this PhD project fell primarily under the "Product Eco Excellence" program, but had natural interlinks to the "Serve the Environment" program. At the outset of the PhD ‘circular economy’ as a concept was not widely known, but during the years it became more apparent in e.g. the Center of Competences, where other divisions were used to working with e.g. life cycle assessment and eco-design topics. Learning from other divisions such as Siemens Healthineers, who established their ‘refurbished systems line’ already back in 2001 was also a part of the PhD project.

Corporate Sustainability provides corporate governance on sustainability topics divided into three areas: Environment, People and Society and Responsible Business Practices. They are more an umbrella organization that creates links between various other Siemens corporate functions such as Corporate EHS, Corporate Supply Chain and Procurement, Corporate Human Resources, etc. The group oversees marketing materials, annual reports, sustainability indices and the environmental portfolio and also coordinates sustainability oriented programs. (Siemens, 2017g) The link between corporate sustainability and this project were mainly related to reporting of sustainability activities.

In terms of sustainability efforts Siemens has had some exiting recent years, including ambitions to becoming carbon neutral, the development of the business to society program and consistent high rankings in sustainability indices. The relevance of this to the PhD project is mainly the movement happening now, where integrating concepts as Planetary Boundaries or Sustainable Development Goals is high on the agenda and business must be shaped to take care of societal issues – e.g. adopting ‘circular’ business models.

For Siemens AG, the company has been included in the Dow Jones Sustainability Index (DJSI) for 17 consecutive years and continuously ranks as one of the most sustainable companies in its industry. The Carbon Disclosure Project (CDP), Corporate Knights, Clean200, MSCI World ESG Index, FTSE4Good series, Sustainalytics are numerous other ratings and rankings Siemens is included in. In recent years they have increased their score for major improvements in climate and environmental protection activities whereas human rights, human capital development, corporate citizenship and social reporting have been noted areas for improvement.

3.2.3.2 Siemens Wind Power

In Siemens Wind Power, the overall EHS responsibility lies with the management, particularly the chief executive officer (CEO). The CEO appointed an EHS Officer who then designated an EHS specialist organization which is dispersed throughout the company in a matrix set up. EHS experts are in market units (onshore, offshore and service), functional units (supply chain management with global and local levels, procurement and technology) as well as regional units (America, Europe and Asia). These experts support the management in fulfilling EHS related tasks. The EHS Officer reports division’s EHS progress and challenges to Corporate EHS on a regular basis.

The PhD project was placed in the Division EHS group, which in short is a governance function, that handles the following topics (related to the PhD):

- Setting minimum standards for EHS include strategy and targets companywide in addition to the roll out of various initiatives and action plans. Governance functions around standards and processes.
- Translating the corporate requirements into the SWP business
- Environmental protection e.g. waste, energy, LCAs, circular economy;
- EHS relevant Training.

As a basis for its operations, SWP employs an integrated management system which includes the latest versions of ISO 14001 for environmental management, OHSAS 18001 for occupational health and safety management and ISO 9001 for quality management.

Starting the PhD project, the EHS strategy, targets and activities of SWP were organized around the four Siemens' EHS programs prescribed by Corporate EHS (see Figure 11). Due to the carve-out of Siemens AG and merger with Gamesa, this has been restructured to six topics of interest, with product stewardship playing a central role addressing the life cycle management perspective of products as a central element and with central links to a more 'circular' strategy.

Figure 11: The new companywide EHS strategic topics at Siemens Wind Power as of 2016

3.2.4 SUMMING UP

Looking at Siemens 170 year history in comparison to the Wind Power Division's nearly 40 years, both companies are in constant change and frequently redefining their organizations based on market trends and customer demands.

Siemens AG seeks to embrace the technological shifts needed to address megatrends such as climate change and resource scarcity through their portfolio of products and services. The SWP's entire portfolio is based around the development of wind turbines and the deployment of renewable energy. The environmental practices described position both Siemens corporate and the wind power division as well structured, preventative and life cycle oriented. End-of-life or 'start-of-second-life-cycle' however, is still in its infancy with mainly Siemens Healthineers as the only case example of a business unit within Siemens AG that have adopted this as a business model. The almost 40 years of age of SWP is interesting as this means that the first generations of wind turbines has reached and are reaching its estimated design life time of 20 years, which makes it relevant to start explore and pilot 'circular economy' business practices. The aim of this PhD is to explore the business potentials from a Wind Power perspective to adopt such business practices.

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4. CIRCULAR ECONOMY AS AN UMBRELLA CONCEPT

This chapter presents the conceptual framework applied in this PhD project. The chapter begins with an introduction to the historical background of the concept of circular economy. This is followed by further introduction to the three identified strategies. Finally, a short section on how circular economy can be seen as a guiding principle from a company perspective to support a sustainable development.

4.1 CIRCULAR ECONOMY AND ITS ORIGINS

Korhonen et al (2018a) states that the notion of the circular economy is based on a fragmented collection ideas derived from a range of scientific and semi-scientific concepts (Korhonen et al, 2018a). Korhonen et al (2018a) highlights concepts as these listed below:

- Industrial ecology (Frosch & Gallopoulous, 1989: Graedel, 1996; Lifset & Graedel, 2001)
- Ecological economies (Boulding, 1966; Georgescu-Roegen, 1971; Daly, 1996; Ring, 1997; Ayres, 1999)
- Industrial eco-systems (Jelinski et al, 1992)
- Industrial symbiosis (Desrochers, 2004; Chertow & Ehrenfeld, 2012)
- Cleaner production (Stevenson & Evans, 2004; Lieder & Rashid, 2016; Ghisellini et al, 2016)
- Product-service systems (Tukker, 2015)
- Eco-efficiency (Welford, 1998; Huppes and Ishikawa, 2009; Haas et al, 2015)
- Cradle-to-cradle design (McDonough & Braungart, 2002; Braungart et al, 2007)
- Biomimicry (Benyus, 2002)
- Resilience of social-ecological systems (Folke, 2006; Crépin et al, 2012)
- The performance economy (Stahel, 2010)
- Natural capitalism (Hawken et al, 2008)
- Concept of zero emissions (Pauli, 2010)

As seen, a considerable number of (semi-)-scientific concepts creates the basis for the circular economy concept, which has been continuously developing. Blomsma & Brennan (2017) divides the emergence and development of the circular economy, with special focus on resource and waste management, into three periods. This is of course a simplified view on the concept as it can be argued that reuse and recycling has been going one since the origins of mankind, in examples where it made sense. However, new attention has been brought to the topic that attracts the attention from both companies and policy makers. The three periods described by Blomsma & Brennan (2017) are:

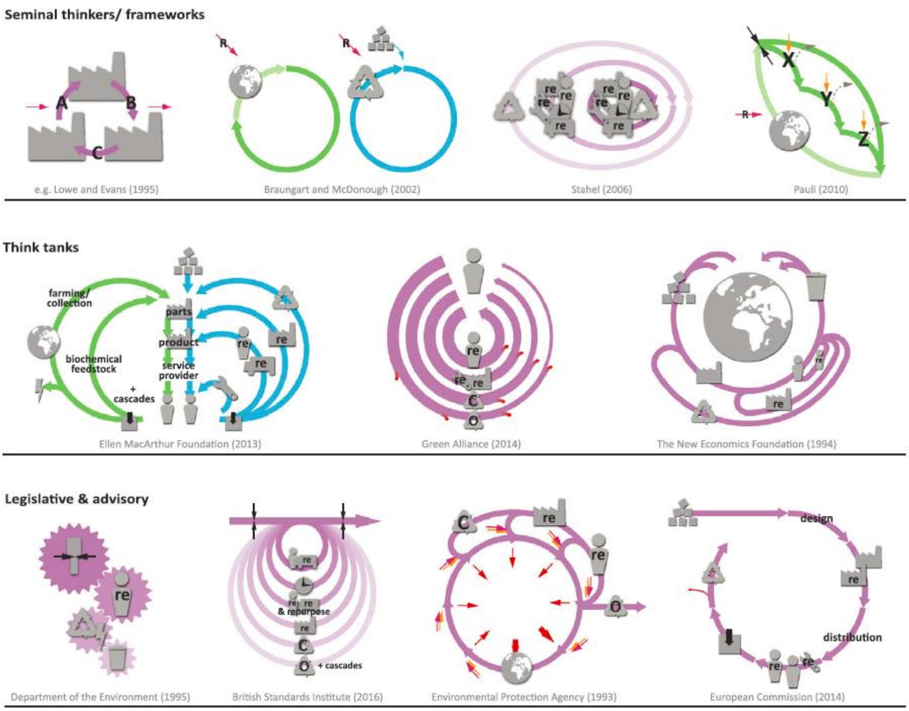
The preamble period (1960-1985): The name of the period refers to being the period before the naming of the circular economy. The main focus of in this period is the polluting effects of waste. Two developments are pointed out as having significant importance during this period. First, a reiteration of the idea of responsible management of natural resources due to publications such as *Silent Spring* (Carson, 1962), *Tragedy of the Commons* (Hardin, 1968) and *Operating Manual for Spaceship Earth* (Buckminster Fuller, 1969), where attention was drawn to the problems of toxicity and scarcity. Further, the realization of the dependence of human and environmental well-being became apparent. These thoughts were coined by Boulding (1966) in *Closed spaceship economy*, and the thoughts were later taken up by Stahel & Reday-Mulvey (1981), who framed the concept of a closed-loop economy. (Murray et al, 2017). The thought also dispersed into the re-thinking of economic and industrial systems e.g. in works as *Limits to Growth* (Meadows et al, 1972)

The second key developments were related to the advances in certain academic fields and the interplay between these (see e.g. Fisher-Kowalski, 2002). This gave birth to new fields and disciplines such as environmental economics and industrial ecology (Frosch & Gallopoulos, 1989). Here the concept of loops and cycles were explored in a systematic manner, and a readiness to learn from nature grew. This laid the ground for later works such as *Biomimicry* (Benyus, 1997) and *ecological economics* (Daly, 1991).

The excitement period (1985-2013): The name of the period refers to that this is the period, where the concept starts to crystallize and gain momentum. The period was dominated by the wider discussion on sustainable development such as The Brundtland Report (WCED, 1987). Sustainable development was mainly framed as an opportunity and addressing these challenges was perceived as a way to manage risks and deliver economic growth and innovation (Hart and Milstein, 2003). There is a change in mind-set to view waste as a resource and a source of value (O'Brien 2008). In this period Pearce and Turner introduced the term 'circular economy' in 1990 (Pearce & Turner, 1990), which was adopted with similar notions in a range of works (e.g. Cooper 1994, 1999).

The strategies for resource management highlighted during this period had a focus to extending the use phase and delaying or preventing landfilling. The strategies were e.g. recycling, urban mining and product-service systems (Blomsma & Brennan, 2017) Related to this, a renewed into to strategies such as product longevity, repair, refurbishment, upgradeability and remanufacturing became apparent (the inner loops) (Blomsma & Brennan, 2017). Further, cascading of resources was brought alive (Chertow, 2000; Pauli, 2010) as well as product longevity strategies such as optimal product life span (Bakker et al, 2014). A shift in perception was further the change that recycling (the outer loop) and waste-to-energy were last resorts of resource management (Ellen MacArthur Foundation, 2013)

The concept also began to find its way into legislation and policies. An example was the Waste Hierachy in the EU (EC, 2008) or in national policies e.g. exemplified by Ghisellini et al (2016) and Murray et al (2017). This period also saw an (partly) adoption of the concept within consultancies such as Cradle2Cradle (Braungart & McDonough, 2002), the performance economy (Stahel, 2006), the Blue Economy (Pauli, 2010) and the Circular Economy (Ellen MacArthur Foundation, 2013). The momentum has built since the interpretation by the Ellen MacArthur Foundation, which has been a key player in bridging the concept to its wider uptake. (Korhonen et al, 2018b). See Figure 12 for a range of models to describe the concept.



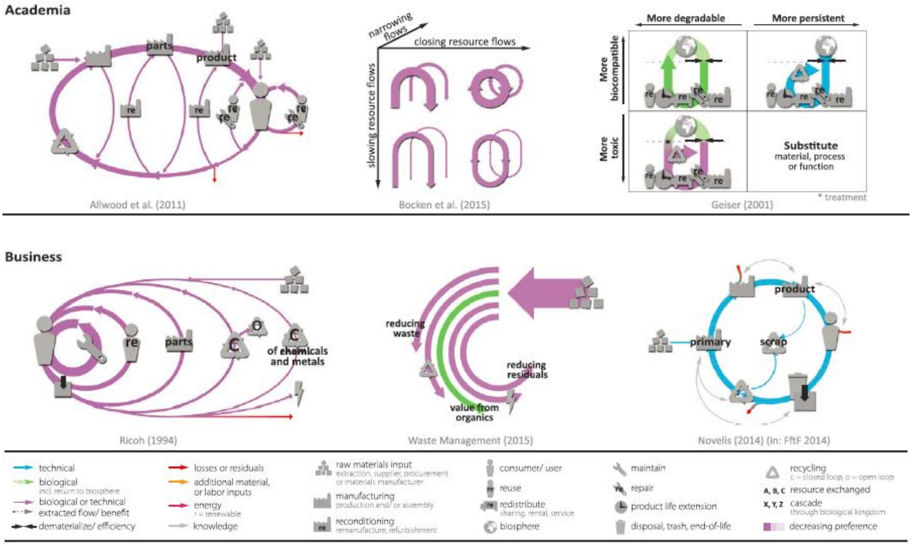


Figure 12: Overview of a selection of models that illustrates circular economy, (Blomsma & Brennan, 2017)

The validity challenge period (2013-present): The period refers to the period, where the different notions and the clarity regarding the concept has to emerge. (Blomsma & Brennan, 2017) Recent literature has pointed out that at least 114 definitions of circular economy are present in the literature (however, not that different) (Kircherr et al, 2017) and the scientific publications on circular economy is increasing rapidly. (Geissdoerfer et al, 2017) Perceived as a sustainable development concept, several authors points out whether the current interpretations are in line with creation of both societal and environmental benefits. (Gregson et al, 2015; Geissdoerfer et al, 2017; Murray et al, 2017) This is supported by Cullen (2017) that argues that circularity requires a holistic strategy that considers sustainability in the context of environmental and social impacts as well as economic ones, to avoid ending up as 'just another perpetual motion dream' (Cullen, 2017).

A common understanding and having metrics and other assessment methods can play a role in consolidating a deeper understanding of the circular economy. Classical industrial ecology tools like life cycle assessment, material flow analysis and input-output can have a central role in this (Blomsma & Brennan, 2017) An important aspect is the need for assessment tools to be useful and meaningful to those who use them (O'Rourke et al 1996). Figure 13 below illustrates the phases the circular economy concept has been through so far as suggested by Blomsma & Brennan (2017)

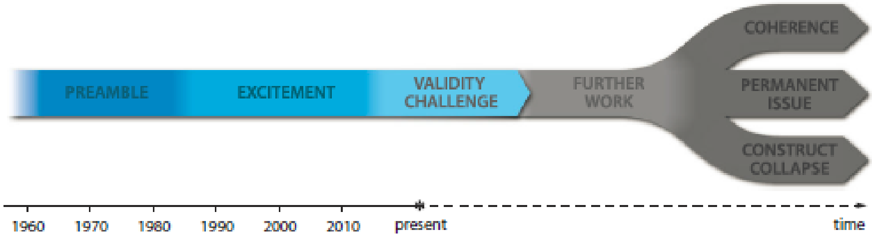


Figure 13: The three described phases of circular economy development (Bromsma & Brennan, 2017)

4.2 CIRCULAR ECONOMY AS A CONCEPTUAL FRAME

For this project, a broad perception of circular economy is taken. Circular economy is an umbrella concept that covers all aspects of *'reducing, reusing and recycling activities in the process of production and circulation'* as noted by Naustdalslid (2014). The circular economy contrasts with the traditional linear economy as the aim is to shift from generating profit from selling artefacts, to generation profits from the flow of materials and products over time. Circular business models can act as an enabler of this. (Bocken et al, 2016) This project adopts the framework on circular design and business model strategies outlined by Bocken et al (2016). In this, the concept of circular economy is broken down into three strategies *narrowing*, *slowing and closing the loops*. (see Figure 14) As defined by Bocken et al (2016) these are:

Narrowing loops: Aimed at using fewer resources per product inspired by *Factor Four* (von Weizäkcer et al, 1998) that aimed to inspire businesses to achieve the same with less resource use. Narrowing is thus not an aim of circularity, but to reduce the resource use associated with products and processes. (Bocken et al, 2016)

Slowing loops: Through the design of long-life goods and product-life extension (i.e.service loops to extend a product's life, for instance through repair, remanufacturing), the utilization period of products is extended and/or intensified, resulting in a slowdown of the flow of resources. (Bocken et al, 2016)

Closing loops: Through recycling, the loop between post-use and production is closed, resulting in a circular flow of resources. (Bocken et al, 2016)

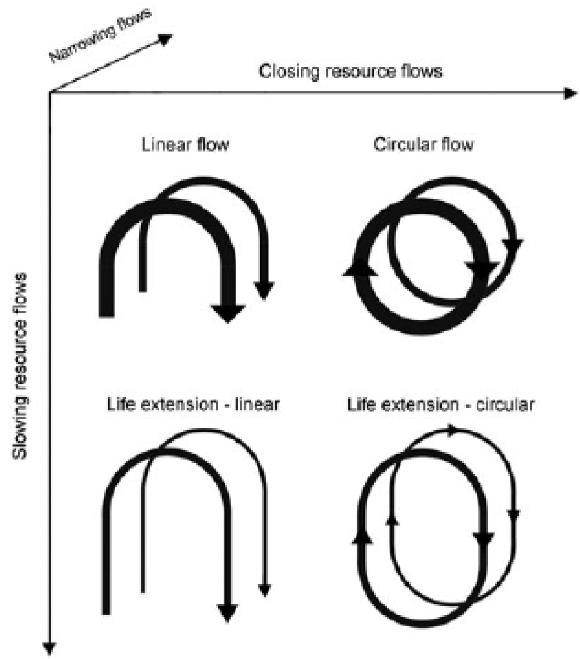


Figure 14: Narrowing, slowing and closing of loops (Bocken et al, 2016)

4.2.1 CIRCULAR DESIGN STRATEGIES

Concerns related to the circular economy should be integrated in an early stage in the product design process due to the possibility of changing specifications later in the process (Skelton, 2017). Requirements for product design, to support narrowing the loops, such as targets for mass per function or alike should be embedded as targets in the product development process (Skelton, 2017). Further, considerations for slowing and closing the loop can also be addressed in the process and supported by business models. Bocken et al (2016) lists a range of circular product design strategies to support slowing (see Table 7) and closing of the loops (see Table 8) as well as supporting business models (Table 10).

4.2.1.1 Slowing the loops

Table 7: Design strategies for slowing loops (Bocken et al, 2016)

Strategies for slowing loops	
Design for long-life products	Design for product-life extension
• Design for attachment and trust	• Design for ease of maintenance and repair

• Design for reliability and durability	• Design for upgradeability and adaptability • Design for standardization and compatibility • Design for dis- and reassembly

Design for long-life products is concerned with ensuring long utilization period of products and consists of three elements.

Design for attachment and trust is referred to as a product that will be loved, liked or trusted longer – sometimes also named emotional durability (Chapman, 2005). Design for durability refers to the physical durability of the product to resist tear and wear without breaking down, whereas design for reliability refers to designing so the product will operate without failures, if maintained in accordance with instructions. (Bocken et al, 2016)

Design for product-life extension is concerned with extension of the use period of products through service loops to extend the product life through reuse, maintenance, repair, technical upgrading and a combination of these. It consists of six elements.

Design for ease of maintenance and repair refers the ability to be maintained to optimal condition via inspection and/or servicing/repair. Upgradeability is defined as the ability of a product to continue being useful by improving the quality, value, and effectiveness or performance. Design for standardization and compatibility is about creating products with parts that fits other interfaces. Design for dis- and reassembly is about ensuring that the product can be dis- and reassembled again, which can support reuse (and recycling) of the materials.

4.2.1.2 Closing the loops

Table 8: Design strategies for closing the loops (Bocken et al, 2016)

Design strategies for closing the loops
• Design for a technological cycle • Design for a biological cycle • Design for dis- and reassembly

Design strategies for closing the loops is divided into design for either a technological or biological cycle. When designing in such a way, the product should be designed so the materials (technical nutrients) can be continuously and safely recycled into new materials and products. This sets requirements to the recycling process (see Table 9), where primary recycling is the intended target of the 'outer loop' in the circular economy and where quaternary recycling is not considered recycling as such, but only energy recovery. Design for dis- and reassembly can support separating the materials – either biological from technological – or to ensure primary recycling. Table 3 lists the recycling classifications.

Table 9: Definition of the four levels of recycling (based on Bocken et al, 2016)

Recycling method	**Definition**
Primary recycling (closed-loop)	Mechanical reprocessing into a material with equivalent properties
Secondary recycling (downcycling)	Mechanical reprocessing into a material requiring lower properties
Tertiary recycling (Feedstock recycling)	Recovery of the chemical constituents
Quaternary recycling (Thermal recycling)	Recovery of the energy from the materials

4.2.2. CIRCULAR BUSINESS MODELS

To support the circular design strategies appropriate business models most be integrated, but achieve the full potential of the (sustainable) value creation. Business models are the determinants of how a company does business and can be seen as one instrument to drive innovation within a company (Bocken et al, 2016). Table 10 offers a list of business model strategies to support circular design strategies.

Table 10: Business model strategies for slowing and closing (Bocken et al, 2016)

Business Model Strategies	**Definition**
Business model strategies for slowing loops	
Access and performance model	Providing the capability or services to satisfy user needs without needing to own physical products

Extending product value	Exploiting residual value of products – from manufacture, to consumers, and then back to manufacturing – or collection of products between direct business entities
Classic long-life model	Business models focused on delivering long-product life, supported by design for durability and repair for instance
Business model strategies for closing loops	
Extending resource value	Exploiting the residual value of resources: collection and sourcing of otherwise wasted materials or resources to turn these into new forms of value
Industrial symbiosis	A process-orientated solution, concerned with using residual outputs from one process as feedstock for another process, which benefits from geographical proximity of businesses

Three business models are listed to support slowing loops.

- The access and performance model – often referred to as product service systems – is associated with the type of business, where the aim is to deliver capability rather than ownership. The service and maintenance part is taken over by the manufacturer, which allows the companies to capture financial benefits from going circular.
- The extending product value is targeting exploiting residual value of products. This means examples where a remanufacturing operation would recover products that have stopped working.
- The classic long life model is concerned with long product life supported by design for durability and repair. The focus is on long-lasting products and high levels of service.

Two business models for closing loops are listed:

- Extending resource value is about the collection or sourcing of wasted material and resources to utilize these in new forms of value

- Industrial symbiosis is the process-oriented version, where waste outputs from one process is feedstock to another process.

4.2.3 CIRCULAR ECONOMY AS PART OF A COMPANY STRATEGY

Using circular economy as an umbrella concept divided into the three strategies can be part of an overall sustainability strategy. Using the definition by Chandler (1996), who define strategy as *' the determination of the basic long-term goals and objectives of an enterprise, and the adoption of courses and action and the allocation of resources necessary for carrying out these goals'*, strategic targets for each of the strategies can be set to support the development with actual measures acknowledging that systemic changes is long-term changes. A further consideration is to measure that the circular economy initiatives contributes to sustainable value creation.

In the following, chapter 5 is the role of narrowing of the loops through a case study. Chapter 6 and 7 addresses the classic long-life and extending product value business models through servitization and remanufacture. Chapter 8-11 address how to support closed-loop recycling, how to extend the resource value and how use of materials like composite material can find secondary application e.g. through industrial symbiosis-like strategies.

As noted by NBS (2012), in order for companies to become more sustainable, they need to i) create financial value, ii) know how their actions affect the environment and actively address those aspects, iii) care about their employees, customers and communities and work to make positive social change and iv) understand these three elements are intimately connected to each other. However, in the following studies, sustainable value creation range wider than creating financial value as triple bottom line indicators are similarly used as a measuring unit (see Chapter 7). The following case studies of the company and its business actions will use the conceptual frame of circular economy to shed light on these aspects.

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5. NARROWING THROUGH DESIGN

This chapter contains a manuscript submitted to 'Journal of Cleaner Production' special volume dedicated to ERSCP2017*, 'Cost as a driver for eco-innovation in the wind industry'* by Jonas Pagh Jensen. An earlier version was used as a conference paper and presented at the European Roundtable for Cleaner Production and Consumption, 1st to 5th of October, 2017, Skiathos, Greece. The current manuscript can be found in Appendix A.

This case study investigates how Siemens Wind Power has developed its most recent offshore wind turbine in the aim of becoming cost competitive, which means generating energy at a levelized cost of energy (LCOE) that is less than or equal to the price of power from traditional fossil fuel based sources. The focus of the paper addresses the material use and environmental impacts related to this development. The sub-research questions that guide the analysis are:

'What characterizes the design and product development of offshore turbines? Can innovations lead to narrowing of the loops and less environmental impacts?'

Conclusions are:

The design and product development can be characterized by an innovation journey, divided into three stages: 1) Redesign, 2) Scale-up and 3) Continuous improvement. The focus of the development process was to drive down LCOE through 'design for reliability'.

The 'redesign' phase led to a new design with lower mass and fewer moving parts. The 'scale-up' phase led to an increase in weight almost following the square-cube law, while the 'continuous improvement' phase meant an increase in resource efficiency in terms of energy output per MW. The findings show that up-scaling is unfavorable in terms of narrowing the loop, while the continuous improvement phase, with special focus on optimization, had a favorable impact in terms of narrowing the loop.

Life cycle assessments performed on this development show an increase in performance on the 'continuous improvement' part, where energy pay back times increased and CO_2-eq. emissions per kWh delivered to grid decreased.

In the analysis, it is shown that five out of eight sustainable design strategies, established in the paper, were targeted in the development process. However, strategies related to choosing low impact materials, optimizing distribution system and optimizing end-of-life aspects were not specifically integrated into the development process.

6. SLOWING THROUGH LIFETIME EXTENSION

Circular economy as a concept has gained attention worldwide. One strategy of the circular economy is prolonging the lifespan of products thus thereby slowing down the throughput of resources in society and reducing the amount of waste.

Back in 1998 Von Weizsäcker et al argued that '*durability is one of the most obvious strategies for reducing waste and increasing material productivity*' (Von Weizsäcker, et al., 1998).

Increasing material productivity or resource efficiency is on the political agenda, but depletion of resources and downcycling of materials has not been a main focus until recently. In fact, much of the materials are wasted as a result of the way consumption and production has developed (Bakker, et al., 2014). To reduce the throughput of materials and energy demands, Cooper claims that a strategy that goes beyond recycling and includes longer lasting products must be applied (Cooper, 2010).

The circular economy, as presented by Ellen MacArthur Foundation, highlights the 'power of the inner circle' and the 'power of circling longer'. It refers to minimizing the material use by 1) maintaining and repairing rather than reusing and recycling and 2) prolonging the life cycles a product. A prolonging of the usage will substitute virgin material inflows (Ellen MacArthur Foundation, 2013).

Cooper highlights that:

> *'A circular economy is a prerequisite for sustainability but may not be sufficient if resource throughput remains high. ... A complementary approach would be to slow down the rate at which raw materials are transformed into products and the products 'used up'* (Cooper, 2010).

Extension of product lifetimes requires support by the business model by maintaining value in the product (Bakker, et al., 2014) or as highlighted by Stahel that '*a shift in focus from resource throughput to asset management'* is needed (Stahel, 2010).

Cooper divides the product lifespans into different categories e.g.:

1) *The technical lifetime* being the maximum period a product has the physical threshold to function. (Cooper, 2010).

2) *The replacement or economic lifetime* being the period from initial sale to the point where the owner buys a replacement regardless of the product functioning or not. (Cooper, 2010)

Increased product life span involves a more efficient use of materials and a slowdown of throughput. The reduction will probably not be offset by increased consumption as the 'resources' put into this is mainly renewable, being man hours for maintenance and repair (Cooper, 2010; Stahel, 2010). However, some products will require new components and transport of the service technician.

The moment for replacement depends on the specific product and technology development (Bakker, et al., 2014). Extending the product lifespan will not necessarily make a positive contribution towards sustainability. If the benefits of product improvements are outcompeted, it may be more favourable to replace it with a more efficient successor. Service and maintenance is often highlighted as one strategy to extend or maximize the lifespan – this is an integrated part of the business model in the wind industry.

6.1 THE LIFETIME OF A WIND TURBINE

A modern wind turbine is typically designed to work for approximately 120.000 hours throughout its estimated life span of 20 years (European Wind Energy Association (EWEA), 2014). However, some larger offshore turbines now have a projected lifespan of 25 years. In Denmark, the average lifetime of the 3216 turbines being decommissioned between January 1977 and November 2017 is 17,70 years with 36 years as the maximum and 0 years as the minimum (typical test turbines). In Denmark, the average age of the existing turbines is 14,6 years with 40 years as the maximum. (Energistyrelsen, 2018)

A wind turbine is a serial system. The reliability of the entire system is the output of individual sub-system reliabilities meaning that the failure rate of the system is the sum of individual sub-system failure rates (Ortegon, et al., 2014).

Specific components within the turbine are subject to more tear and wear. Generally, the moving parts are worn out faster than static parts, and exposed components are worn out faster than shielded components. Blades and gearboxes have historically been considered to wear out the fastest (WMI, 2014).

The actual lifetime of the turbine depends on the quality of all the components of the turbine, their assembly and the environment the turbines are placed within such as onshore, offshore, wind, turbulence, air density, humidity etc. The turbulence will in general be lower at sea as there are no obstacles (WMI, 2014).

6.1.1 THE CAPACITY FACTOR

The capacity factor during the lifetime of a wind turbine is essential, when considering extending the lifetime, as it must remain at a certain level to make it feasible to run the wind turbines.

The capacity factor is calculated as:

> *'the ratio of the amount of electricity actually produced by a turbine or wind farm over a period of a month or a year divided by the amount of output that would have been produced had it operated at full nameplate capacity for the entire period. This is expressed as a percentage, so that reported capacity factors lie between 0 and 100'* (Hughes, 2012).

The capacity factor for wind power has historically been assumed in the range of 30–35 % of the name plate. Some studies have however shown examples of mean values below 21 % (Boccard, 2009), but new wind turbine parks are however often calculated with an expected capacity factor between 37 – 40 % (Siting Specialist, 2015). In chapter 6.3 a deep dive into the capacity factor of a 1 MW turbine is provided.

Staffell & Green (2013) lists five factors that influence the capacity factor:

1) *Machine availability*: Downtime of the turbines or the electrical infrastructure can affect the output by 4 to 7 % in decline (Staffell & Green, 2013).
2) *Operating efficiency*: Sub-optimal control systems, misaligned components and electrical losses within the farm can reduce the output by 2 % of the turbine (Staffell & Green, 2013).
3) *Wake effects*: Wind farms are affected by power loss as neighbouring turbines increase turbulence and reduce wind speeds. The output can drop in the area of 5 to 15% (Staffell & Green, 2013)
4) *Site conditions*: Imperfections in the local environment like e.g. turbulence intensity and terrain slope will impact the output. These are site specific and will vary, but are estimated to reduce output by 2 to 5% plus 1 % per 3% increase in turbulence intensity (Staffell & Green, 2013).
5) *Turbine ageing*: Different factors of decline in output as the turbines age. (Staffell & Green, 2013).

6.1.1.1 The capacity factor over time

A thorough study on wind turbines in UK and Denmark by Hughes concludes a significant decline in the average capacity factor (adjusted for wind availability) as the turbines ages. It concludes that the capacity factor in the UK declines with 0.9

percentage points per year the first 10 years of operation starting at approx. 24 % and falls to 11 % at age 15 (Hughes, 2012).

Another study by Staffell and Green that analyses the same data concludes that the decline with age is 0.45 percentage points per year, which is quite different from Hughes. (Staffell & Green, 2013). They further claim that farms built before 2003 have a decline rate two to three times higher than turbines built after 2003 (Staffell & Green, 2013), which is indicating a more reliable technology today than earlier.

An analysis by McKinsey & Company finds that performance is unrelated to the age of wind parks (and of the manufacturer). However, factors such as e.g. dirt in the blades can prevent the wind force from being transmitted to the blades and the generator, which results in lower output (McKinsey & Company, 2008).

There are however strategies to maintain a high performance and thereby make a basis for lifetime extension. Lifetime extension can follow different strategies. These are analysed below and the environmental impact of lifetime extension is assessed.

6.2 ROUTES FOR LIFETIME EXTENSION

The following section will analyse the present strategies of 1) service/maintenance, 2) reuse/redistribute and 3) refurbish/remanufacture, to maintain a certain level of capacity factor.

6.2.1 SERVICE/MAINTENANCE

A study by Ortegon et al (2014) presents that the number of failures, the downtime and the cost will be drastically reduced with regular maintenance (Ortegon, et al., 2014).

The service concept has been gradually integrated in the business model of the OEMs (Original Equipment Manufacturers) in the wind industry.

In SWP, diagnostic models as part of the service industry has been utilized since 1998, when it was decided to add diagnostic sensors into the turbines. (Siemens, 2014b)

Supervisory control and data acquisition (SCADA) systems are integrated parts of modern wind turbines, which makes it possible to remotely monitor information such as electrical and mechanical data, operation and fault status, meteorological data and grid station data constantly. It regulates the active power output of the turbine and is an essential part in keeping the capacity factor as high as possible. Further, turbine condition monitoring (TCM) systems, which makes it possible to perform precise condition diagnostics based on vibration, which can give an early warning if any components are having problems and thereby reduce maintenance costs and optimize energy output (Siemens Wind Power, 2014a).

Using data models, the diagnostic system is able to solve 85% of all anomalies remotely (within 10 minutes), where a technician would have been needed otherwise. Further, 98% of anomalies can be diagnosed before sending a technician to the turbine, which means the technician will bring the right spare parts, tools etc. and thereby minimizing downtime. This is a huge support in minimizing cost in events, where wind turbines are installed in locations characterized by extreme climates like isolated mountain peaks, far offshore, or in desolated environments. (Siemens, 2014b)

The diagnostic areas are divided into three areas – reactive, proactive and interactive. The reactive can be referred to, when an alarm occurs and forces the turbine to a halt. This is then dealt with reactively. Proactive diagnostic services is based on the experience of the diagnostic model, where proactive measures are taken to avoid downtime by planning maintenance, repair, replacement etc. in advance and thereby avoiding failures and downtime. The interactive diagnostic services focuses on solving issues to keep the turbine in operation based on data inputs from the turbine. (Siemens, 2014b)

The diagnostic models that are being used are based on learning from the vast amount of data being gathered. By applying methods such as neural networks, mathematical models are created to create the diagnostic models. However, the impression is that the data provides a range of models to support lifetime extension, increased availability and energy output. (Siemens, 2016)

The models to understand these patterns are one part of the service and maintenance strategy to move from corrective and calendar based maintenance to condition-based maintenance. To achieve this monitoring systems needs to be deployed in the turbine. The focus is to monitor even small components e.g. through a system to monitor the transistor been developed, which detects failures before it overheats, which can prolong the lifetime of the wind turbine (Frandsen, 2014) or creating the platforms to handle the monitoring like e.g. the ROMEO consortia. (EU, 2017)

Services and O&M are becoming an more and more important part of the companies' revenue streams as installed capacity grows and turbines comes out of their warranty period and the wind industry is moving from a period of solid growth to one of high, steady volumes. (Blackwell, 2017) The recent trend is the change in the business model to also service and maintain other brand's turbine – the so-called multibrand strategies. (Blackwell, 2017)

6.2.2 REUSE/REDISTRIBUTION (NEW LOCATION)

Reuse/redistribution can be a option, when e.g. a wind turbine reach its economic life at one site (often linked to the time period with subsidies), but not its technical life.

This market has been dominated by independent service providers. In the OEM field. Vestas' 'Wind for Prosperity'-programme (Vestas Wind Systems A/S, 2013) have been an attempt to engage in this market. The 'Wind for Prosperity' aimed at *'combatting energy poverty and deploy green technology in developing countries' by committing to source and factory-refurbish a selection of wind turbines that have favourable dimensions for transportation and erection'* (WindforProsperity, 2014). As the main market for 'Wind for Prosperity' was third-world countries, Vestas mainly focused on 'small' wind turbines (WindforProsperity, 2014). Vestas teamed up with ABB to deliver wind power to local communities (Wang, 2014). However, the programme only ran for a few years and was later closed again.

6.2.3 REMANUFACTURING/REFURBISHMENT

Remanufacturing of wind turbines is another possibility. Interest in refurbishment from an owner perspective can come from permitting e.g. height restrictions on some properties (Dvorak, 2014)

Experience with other remanufactured products indicates that when costs of a remanufactured product exceed 70% of a new product, the new product is preferred. (Cooper, 2010)

Ortegon et al (2014) states that the effective age of a remanufactured wind turbine is estimated to additional six years (Ortegon, et al., 2014).

Siemens Gamesa offers an 'aging fleet solution' offering a service program that focuses on lifetime extension of wind turbines. The wind turbine life-extension program consists of a series of structural reforms and a monitoring system designed to prolong the useful lives of wind turbines at its current location (Gamesa, 2014).

The programme includes both some Gamesa turbines, but also turbines from competitors. The estimation is to add a 10 year life extension compared to the estimated end-of-technical-life. The focus is mainly on <1MW turbines as they are reaching the 20 years design technical life at the moment, but plans to include larger turbines. It is expected that the cost will be half of the extra revenue generated by the life extension (Dvorak, 2014). Gamesa is taking part in the European Union-sponsored project, SafeLife-X that seeks to develop effective solutions for minimizing the ageing of industrial infrastructure (Gamesa, 2014).

Other OEMs has also started to look into this side of the business. Examples are:

In May 2014 Vestas introduced their PowerPlus™ programme (Vestas Wind Systems A/S, 2014), which focus is upgrade of existing turbines to increase annual energy output (AEP). The programme offers upgrades within three different areas and depending on the turbine and the number of upgrades, the AEP is estimated to increase by 2.3 % - 6.8 %. It can potentially make it feasible to keep old and smaller turbines running for some extra years (Dvorak, 2014).

General Electric has developed an upgrade on the blades, so their 77m blades can be replaced with 91m, which will increase the swept area by 40% and can boost the AEP by approximately 20 % (Dvorak, 2014).

The routes for lifetime extensions are becoming digitalized by companies like 'Spares in Motion', which have received the award 'Best Industry Newcomer (Froese, 2015). It acts as a e-trading platform for the services used for lifetime extensions. It reduces the complexity, cost and lead time for these services and thereby does this innovative business model improve the possibility of lifetime extensions. The has recently also been taken up by an OEM like Vestas. (Andersen, 2018)

The different strategies all present possible ways to optimize the turbine during its lifetime and thereby making it attractive to extend the lifetime of the turbine. The larger the turbine is the more revenue is created by the upgrade.

6.3 THE 1 MW TURBINE CASE EXAMPLE

The best strategy from an environmental perspective is not straightforward. The assessment of routes for lifetime extensions have to be done on an individual basis as different turbines on a wind farm see different types of loading, which leave them at different stages after e.g. 15 or 20 years (Dvorak, 2014). In 2012, Kenetech chose to repower 235 turbines after an analysis, whereas EDP Renewables reviewed their 153 wind parks and chose to extend the project life of the parks from 20 to 25 years, which highlights the different potential strategies. (Houston & Marsh, 2014). These are - still – affected by national legislations like e.g. in the US, where it is possible to renew the production tax credit period by replacing 80 % of the value of the turbine with upgraded components. (Energy.gov, 2018)

However, as part of this project, a technical and economical assessment of remanufacturing the existing fleet of turbines reaching its design lifetime, was carried out.

First of all, the model type was chosen. For this, a 1/1.3 MW turbine was chosen as the first of these were installed in 1998 (reaching 20 years of lifetime). In total, close to 1900 turbines were installed with the main part installed in Europe (Germany, France, Denmark, Norway and UK) and a minor part in USA. The turbines are technological similar with the main difference in the frequency delivered to the grid by the turbines (50hz vs. 60hz).

Based on Danish data, 149 of these turbines are still in operation in Denmark with all of these being installed between 1999 and 2002. The average capacity factor of these over their lifetime has been 21.5 % with a minimum of 13.9% and a maximum of 31.9

% (years with production of 0 has been excluded from the analysis) (based on Energistyrelsen, 2018). This shows variations in the capacity factor due to the location. An interesting trend on these turbines, is the capacity factor over time (see Figure 15). . By adding the trend line, it can be seen that the trend is that the capacity factor is increasing from 1998 to 2016.

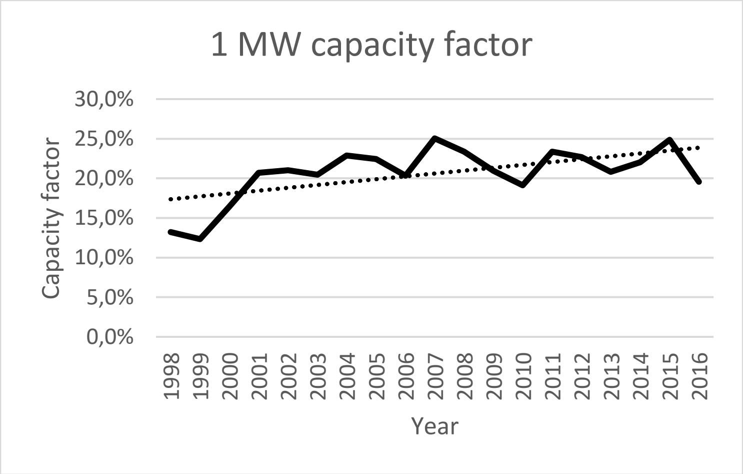

Figure 15: 1 MW turbine fleet capacity factor per year (based on Energistyrelsen, 2018)

A possible explanation could be related to problems in the early age of the turbine. By excluding the first five years after the introduction of the turbine, the trend line shows that it is more or less stable, but also not showing a decrease in the capacity factor as the turbines age (see Figure 16).

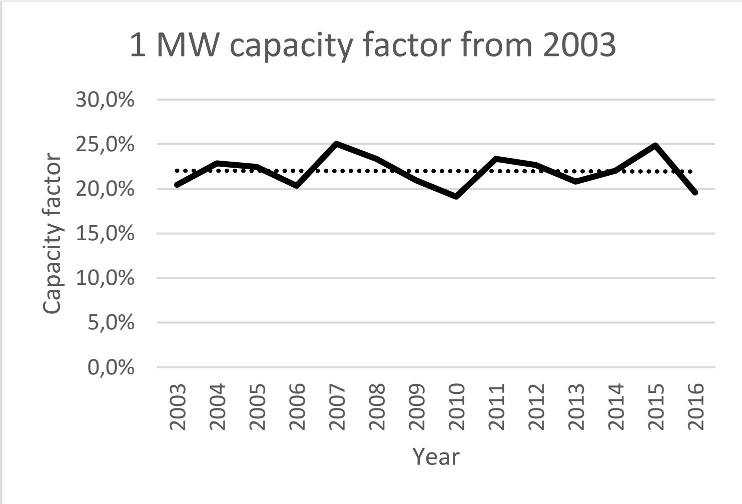

Figure 16: 1 MW turbine fleet capacity factor per year since 2003 (based on Energistyrelsen, 2018)

However, at some point in time, it may be relevant to replace these turbines with modern turbines with an expected higher output (if planning restrictions permit) or when the turbine components have experienced loads that will leads to failure.

During an expert workshop, the experiences of the fatigue on the components were analyzed as well as the potential component exchanges needed to add additional 10 years of lifetime (in a scenario, where the turbine is decommissioned, remanufactured and installed at a new site).

The turbine was divided into nine main components and assessed based on these.

Blades – based on the track record of the turbine, the blades are still in good condition. No exchange of blades would be need. Repair of potential cracks can be done, but the strength of these will not be better than the original structure. A new coating is suggested. However, the failure of these would follow a Weibull distribution, but as the blades does not have started to fail, the actual remaining lifetime cannot be assessed, but ten years is assessed to be within the possible range.

Hub – no structural damages that hinders ten years of extra lifetime is known in the hub. However, parts such as bearings, oil parts, rubber parts, valves, accumulators and hoses supposedly would need exchange.

Main bearing / shaft – it will probably see some cracks in the shafts after 20 years of operation, but it will probably be possible to run for another ten years. However, a complete remanufacture of the component is assessed preferred.

Gear – it will need a testing of the gear. The level – from spin test to full load test – can be decided based on visual inspection. Sub-components such as lubrication system, filters, oil pumps, hoses and cooling system would need replacement to run for additional ten years.

Generator – the main failures are related to lightning strikes, but if no failure, replacement of the cooling system, coupling as well as testing the measuring system is the main remanufacturing steps to be undertaken.

Hydraulic system – it has seen some wear and tear and rubber parts, valves, pumps, hoses, accumulator, filters needs replacement to operate for additional ten years.

Nacelle cover – would need to be checked for structural damages. Further, replacement and exchange of wind vane, anemometer, rubber parts, air inlets and hatches is expected.

Yaw system – it is expected that the yaw system has experienced a lot of tear and wear. The yaw rings are most likely to be exchanged as well as yaw years (if not moved into a new position) and motors.

Tower – is expected to be directly reused. Internal staircases and platforms might be exchanged, as well as internal cables. Bolts would need inspection before reuse.

Further, considerations like integration of a new **control system** and **converter** are recommended to optimize the operation, but would need a cost-consideration to determine the feasibility of these (relative high-cost) components.

A few of the spare parts recommended for exchange are assessed to be out of production, but with available drawings these might be available for production again. Spare part availability is an area for further research.

Apart from the technical evaluation, there are other parameters to consider, which are:

Grid compliance – what are the national grid requirements, where the remanufactured turbine is to be installed. If requirements for aligning voltage and frequency with the grid, integration of a full converter is needed as this is absent in the original turbines. However, this can be integrated and will also impact on the power curve (and thereby potential output) to be higher.

Insurance – typically, insurance for remanufactured wind turbines is identical to those for new wind turbines. However, not all insurance companies are offering this option. Reputability of the manufacturer is known to be a parameter that can influence this decision. (Ricardo Energy & Environment, 2016)

Business model – the business model which the product is being sold within. Choosing a business model, in which the operation and maintenance price is fixed is one way to de-risk the investment for the buyer.

Learnings from this workshop show that it is possible to remanufacture the turbines and thereby extend the lifetime from a technical point-of-view. Determining the price and lifetime (and associated energy output) determines the feasibility of this.

In an assessment of the used wind turbines for sale on the online marketplaces like 'Spares in motion' and 'Windturbines marketplace' February 2017 to May 2017, estimations of the re-sale value of the turbines based on nameplate capacity is made. This shows an offering price of 107,000 € per MW, when making linear regression (see Figure 17). However, it can also be seen that the prices vary widely depending on functionality, age, brand and similar. However, for this, an average is used as an indicator.

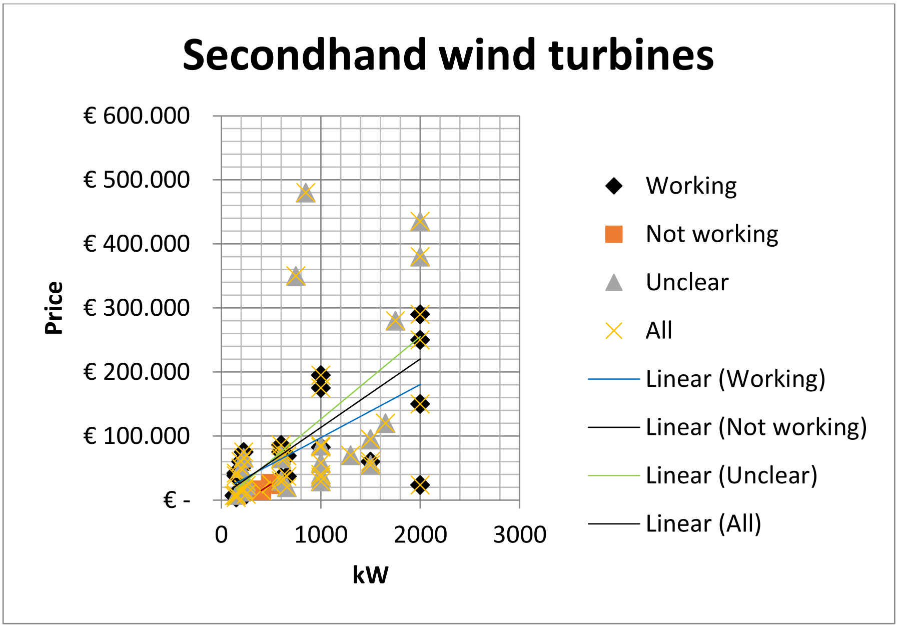

Figure 17: Offering price of used wind turbines on 'Spares in Motion' and 'Windturbines marketplace' from 1st of February 2017 to 8th of May 2017

Based on this, estimations of the expected LCOE can be made. Two scenarios have been defined.

Scenario 1: Total cost of remanufactured turbine equals 345,000 €, hub height 80 meter, OPEX 20k €/MW p.a., availability of 96 and lifetime 10 years.

Scenario 2: Total cost of remanufactured turbine equals 495,000 €, hub height 80 meter, OPEX 20k €/MW p.a., availability of 96 and lifetime 10 years.

The analysis show that in the range, where capacity factor is around 21% (as the average in DK), the LCOE of scenario 1 is 32.0€/MWh and the LCoE of scenario 2 is 41.5€/MWh (see Figure 18), which is significant lower than e.g. LCOE of recent offshore prices (see paper 1).

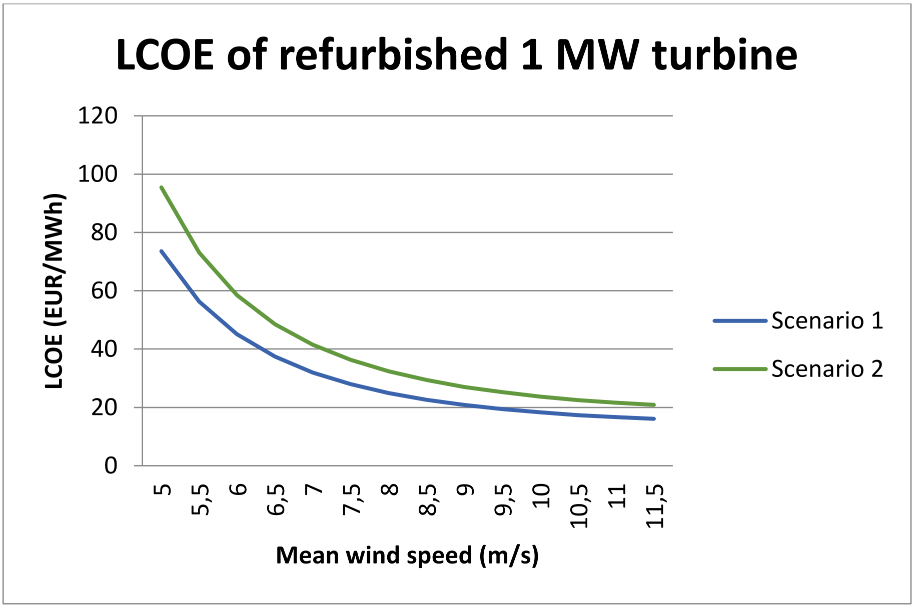

Figure 18: LCOE of remanufactured 1MW turbine

The assessment has shown that given the right circumstances, remanufacturing of the wind turbines is technically and economically feasible. However, there is still a range of business challenges that needs to be addressed e.g. the sale of remanufactured turbines, availability of turbines versus sales volumes, warranty issues and similar. These have not been explored by this project. Finally, assessing the impact of lifetime extension is interesting in term of sustainable value creation

6.4 THE ENVIRONMENTAL IMPACTS OF LIFETIME EXTENSION

An assessment of the environmental impact on extending the lifetime can be seen below in Table 7. The calculations, made by the author, are based on a life cycle assessment for a 3.2MW onshore wind power plant by Siemens Wind Power, and the data behind the lifetime calculations are provided by Siemens Wind Power. Data from the 3.2 MW turbine have been used as this were available to illustrate the impacts of lifetime extension. The absolute numbers from 1MW turbines will most likely differ from these, but the general trend is assessed to be similar.

Table 7: kg CO_2-eq. emission per MWh delivered to grid and times the energy is paid back for different lifetimes of wind turbines

Lifetime	**10 years**	**15 years**	**20 years**	**25 years**	**30 years**
kg CO2/MWh	8.7	5.8	4.4	3.5	2.8
Times energy is paid back	29	43	57	72	86

An extended lifetime will have a positive impact on the carbon footprint and the amount of times the energy is paid back will increase significantly. This is partly due to that the energy needed to maintain the turbines is relatively small compared to the energy output.

6.5 CONCLUSION

The way of doing business is changed by moving away from traditional ’take, make and dispose’ pattern towards focusing on product durability by integrating asset management. Specifically, the manufacturer has the possibility to add value through the lifetime of the product, which opens up a venue for new business possibilities.

Different studies show as outlines different results regarding performance over age for wind turbines, but all agree it is possible to maintain a high performance and even upgrade the wind turbine over time. In the case of wind turbines, different routes of asset management are possible to achieve a long product life. The options are; i) service/maintenance, ii) reuse/redistribution or iii) refurbish/remanufacture. The options include different management strategies.

The OEMs have over the past decade entered the business of service and are getting more and more sophisticated and have currently shown different potentials of prolonging the lifetime and thereby improving environmentally and economically.

An extended case of a 1MW turbine shows that, under the right circumstance, remanufacturing is both technically and economically viable.

The lifecycle assessment of a scenario with regular service/maintenance and lifetime extension shows that the environmental benefit from prolonging the lifetime is significant. Environmentally, it is worth maintaining the wind turbine to maximize its technical lifetime. However, further analysis could be needed, when replacement with larger and more efficient turbines are ideal – both from a manufacturer or policy perspective.

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7. SLOWING THROUGH REMANUFACTURE

This chapter contains a manuscript submitted to 'Journal of Cleaner Production' *'Creating Sustainable Value Through Remanufacturing: Three Industry Cases'* by Jonas Pagh Jensen, Sharon Prendeville, Nancy Bocken & David Peck. The manuscript can be found in Appendix B. The manuscript was made as part of the research stay at TU Delft.

In the article, remanufacturing as an activity for sustainable value creation is explored through three case studies. Remanufacturing is a proposed strategy to develop circular business models with the aim of slowing resource loops. If remanufacturing is to occupy a central role in the circular economy it needs to be considered from a series of complementary and synchronous business activities. Thus, the aim of this article was to investigate how such an integrated perspective could drive sustainable value creation within the context of remanufacturing business models. The sub-research question that guides the analysis is:

'*Can an integrated perspective drive sustainable value creation in remanufacturing contexts?*

To answer the research question, a set of triple-bottom-line indicators across the chosen cases were mapped. The work contributes to the field by also mapping a set of business mechanisms (e.g. warranties, service strategies and partnerships) that can be utilized to co-develop necessary activities in unison for a successful remanufacturing strategy. In certain cases, remanufacturing was found to potentially add to the triple-bottom-line through such an integrated strategy. However, each of the firms investigated are investing in remanufacturing predominantly for profitability and market protection measures and therefore environmental and social components of the triple-bottom-line must more proactively be considered and stimulated

8. CLOSING THROUGH PRODUCT STEWARDSHIP

This chapter contains a paper published in '*Procedia Manufacturing',* Volume 8, 2017, pp. 377-384*, 'Enabling Circular Economy through Product Stewardship'* by Jonas Pagh Jensen & Arne Remmen. The manuscript can be found in Appendix C.

In the paper, research on how sustainable manufacturing extends beyond the manufacturing process to include the supply chain, across multiple product life-cycles as well as end-of-life considerations, is presented. Companies can gain a competitive advantage by applying sustainability manufacturing for environmental friendlier products and operations. Industry 4.0 sets new requirements for becoming a sustainable manufacturer where data management, the 'Internet of Things' and extended product service systems are tightly linked with traditional manufacturing processes.

The sub-research question that guides the analysis is:

Which strategies has been taken by the automotive, shipping and aviation industry to address end-of-life challenges? What lessons can the wind industry learn from a benchmark with these industries?

The automotive, aircraft and ship manufacturers have either been regulated or have voluntarily adopted product stewardship initiatives to support high quality, end-of-life management. Different 'product stewardship' and 'end-of-life' strategies that can support the circular economy are highlighted in the paper. The analysis was used as an inspiration for what could be relevant to implement in the wind industry to ensure recycling of the wind turbine components and actions to support future circular economy ambitions, expectations and strategies.

Common conclusions that can be made are:

- Most of the industries see an increase in complex materials e.g. composites
- Developing best available practices help to increase the rate of recycling
- Data and material information management plays a significant role in the business model for circularity
- An increased OEM focus benefits the secondary market

9. CLOSING THROUGH DECOMMISSIONING AND RECYCLING

This chapter contains a paper submitted to the journal *'Wind Energy'* in February 2018 named *'Evaluating the environmental impacts of recycling of wind turbines'* by Jonas Pagh Jensen. The paper is currently being reviewed by editors of the journal. The manuscript can be found in Appendix D.

In the paper, research on decommissioning and recycling of wind turbines is being presented with special considerations given to the environmental aspects. This includes cradle-to-gate life cycle inventory analysis of the materials, embedded energy and CO2-eq. emissions. The research question that guides the analysis is:

'How does the decommissioning process of wind turbines work? What is the environmental impact of recycling the materials at end-of-service-life?'

The findings show established recycling methods are present for most of the materials and that recycling of a 60MW wind park at end-of-service-life provides environmental benefits as well as lowering the natural resource use and securing resources for further use in the future. The energy savings by recycling is estimated to 81GJ and the reduction in emissions related to the recycling of wind turbine material is estimated to 7351 ton CO_2. The comparisons show how much benefit can be gained from recycling wind turbines whilst preserving resources for future generations.

Common conclusions that can be made are:

- Offshore decommissioning is still in its infancy
- Regulations are beginning to require decommissioning assessments already in the tender process of the project
- A large portion of the turbine is recyclable
- Composite materials and permanent magnets are the most challenging parts to recycle
- There are considerable CO_2 and energy savings related to recycling of the wind farm

10. THE BLADE CHALLENGE IN CLOSING THE LOOP

This chapter contains a manuscript submitted to *'Renewable and Sustainable Energy Reviews*' in 2017 named '*Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy'* by Jonas Pagh Jensen and Kristen Skelton. The manuscript can be found in Appendix E.

In the paper, research on the handling of end-of-life blades is presented. The wind power industry is a fast growing, global consumer of glass fiber-reinforced plastics (GFRP) composites, which correlates with the industry's rapid growth in recent years. Considering current and future developments, GFRP waste amounts from the wind industry are expected to increase. Therefore, a sustainable process is needed for dealing with wind turbines at the end of their service life in order to maximize the environmental benefits of wind power. Most components of a wind turbine such as the foundation, tower, gear box and generator are already recyclable and treated accordingly. Nevertheless, wind turbine blades represent a challenge due to the type of materials used and their complex composition. The sub-research questions that guide the research are:

What are the processes for handling blades at end-of-life? What are the potential applications for secondary use?

The research finds that there are a number of ways to treat GFRP waste, depending on the intended application. The best available waste treatment technologies in Europe are outlined in this paper. However, there is a lack of practical experiences in applying secondary materials in new products. A Danish innovation consortium was addressing this waste with a predominant focus on the blades from the wind power industry. The outcomes from the consortium and the various tested tools are presented in this paper as well as the secondary applications that were proposed. The outcomes are structured using Ellen MacArthur's circular economy diagram. The adjusted diagram illustrates the potentials for a continuous flow of composite materials through the value circle, where secondary applications were developed in respect to "reuse", "resize and reshape", "recycle", "recover" and 'conversion'. This included applications for architectural purposes, consumer goods, and industrial filler material. By presenting the outcomes of the consortium, new insights are provided into potential forms of reuse of composites and the practical challenges that need to be addressed.

11. THE MAGNET CHALLENGE IN CLOSING THE LOOP

This chapter contains a manuscript submitted to the journal '*Journal of Cleaner Production*' in January 2018 named *'NdFeB magnets and the wind industry. Towards circularity?'* by Jonas Pagh Jensen. The manuscript can be found in Appendix F.

In this paper, the production of NdFeB magnets for use in wind turbines is being addressed. Focus on recovering value resources such as rare earth elements are high on the agenda both within the company and within the EU. Rare Earth elements play a crucial role in the development of direct drive wind turbines as these utilize NdFeB permanent magnets. The sub-research questions that guide the research are:

How has the challenge of rare earth elements in permanent magnets in the wind turbine industry been addressed? Can strategies for end-of-life benefit both the environment and the economy?

The findings show that:

- Through co-development of magnet material of smaller sizes, the efficiency of the magnet increases and thereby the grade of the magnet. This leads to less material use per MW.
- A manufacturing step to avoid the grinding process has been developed, which avoids manufacturing waste of up to 30% of the magnet volume.
- Due to encapsulation and direct cooling of the magnets, irreversible flux losses are avoided during the operation phase.

Regarding end-of-life management

1) Several recycling technologies exist for magnets recycling.
2) Demagnetized magnets are sold at 11-12 $ USD / kg.
3) Recycling plants are needed for scale and improvement in recycling efficiency.
4) Life cycle assessments show positive impacts on global warming potential and energy usage when recycling the permanent magnets.
5) A large amount of NdFeB magnets are available within the generator.
6) NdFeB magnets in the generator are dismountable and recyclable as the design of the generator allows for dismantling without harming the magnets.

12. CONCLUSION AND RECOMMENDATIONS

This thesis examines how circular economy can contribute to sustainable value creation in the wind industry. The circular economy has been defined by three strategies being narrowing, slowing and closing. This constitutes the main research question of this thesis. The empirical parts of the thesis have been targeting each of the loops within the circular economy to estimate how each of the loops contributes to sustainable value creation.

A series of literature reviews related to each of the loops is conducted. These are integrated in the papers and the focus of these is dependent on the case studies. The empirical case studies were shaped by the conceptual framework (the circular economy) as well as the contextual framework (the company).

This chapter has several purposes. First of all, the main findings are presented of the empirical case studies and based on these provide an overall answer to the main research question. Additionally, the findings of the longitudinal study not covered in the research questions will be reflected on here. Finally, recommendations for further research is proposed.

12.1 NARROWING, SLOWING AND CLOSING

To answer the main research question '*What are the potentials of narrowing, slowing and closing the loops for Siemens Wind Power products as part of a sustainable value creation strategy?'* each of the parts are synthesized as the answer to the main research question.

In this, synthesized should be perceived as an attempt to answer the main research question via a series of sub-questions and sub-answers. In general, the findings of the different case studies are restricted to the level of and assumptions made with respect to these cases in their specific contexts, and not generalizable. However, each of the parts II, III and IV has analyzed parts of the potentials for each of the respective strategies via a set of sub-questions. The hypothesis applied is that the sub-answers to these questions also seem defendable at the level of and for that respective part of the main research question. Other parts of the study are based on extensive literature study and of more generic nature, therefore their generalizability is more obvious. Altogether, to find a more definite answer to the main research question, a much broader, quantitative set-up and case base is required, to test and validate the outcomes. Therefore, the findings here presented is a first indication of an answer, with a tentative nature.

As shown in part II, narrowing of the loops is an integrated part in the product development process in order to minimize the cost of the turbine in the aim of lowering the levelized cost of energy. Traditional scaling up has an unfavorable relationship between energy output and material use due to the square-cube law, which means that innovation is central in developing turbines with higher output without increasing the mass too much. The development process of the 8MW offshore direct drive turbine was analyzed and it was found that it went through three phases being; 'redesign', 'scale-up' and 'continuous improvement', where especially the redesign and continuous improvement phases were targeting narrowing the loops.

Through the case study of the development process from 6MW to 8MW turbines for offshore purposes, it is found that it has been possible to increase the annual energy output by 20 %, whilst maintaining the same mass. This has been achieved by optimizing sub-systems such as magnet composition, cooling system and electrical system. When quantifying the environmental impacts in terms of CO_2-eq. emissions per kWh delivered to grid it was found that this was actual lowered from 7.1 gram to 5.8 gram. Further, the energy pay back time was reduced from 9.5 months to 7.6 months.

In short, the narrowing loops strategy is central to lower the LCOE, which is a pre-requisite to remain competitive and at the same time, this lowers the environmental impact per kWh delivered to grid thereby contributing to sustainable value creation. The findings of this research are specific to the direct drive technology within the wind industry, however, the research strategy could be applied at other manufacturers, where the main parameter of competition is LCOE (due to the change to an auction-based incentive scheme for infrastructure projects in many countries.).

By assessing *what type of value creation narrowing loops contribute to,* it is found the narrowing loop strategy is a core parameter within the industry and in the competition with other sources as this is a significant part of the CAPEX in the LCOE from wind energy. Narrowing the loops will be central in future development strategies, which is positive in terms of the related environmental impact. However, in a market situation that is changing to auction-based market schemes, the profit margins on the turbines itself is under pressure and could therefore be combined with slowing and closing loop strategies.

Part III shows that different models for slowing the loops can be applied. From the OEM side, digitalization and use of diagnostic tools based on data is driving the trend in the service business. Predictive maintenance instead of reactive has been the focus of this, to minimize the number of visits to the turbine (often referred to as mean-time-between-visit) and to schedule the maintenance and repairs to times of low wind (or low electricity prices, if no subsidy schemes are in place). The general trend is towards smart planning and optimization. This can also be applied to smart management of the turbine to e.g. reduce the loads in high wind and thereby provide the basis for extending the ***technical*** lifetime.

Lifetime extension (either on the same site or new site) is still in its infancy from the OEM side, but with some examples worldwide to learn from. The business models for these differs geographically as national support schemes can support these e.g. extension of the PTC in the US. The scientific literature indicated a small decrease in efficiency of the turbine as it ages, but an assessment of a specific SWP turbine model showed no loss in efficiency as it ages.

An assessment of a full turbine remanufacture shows that it is possible to extend the technical lifetime by replacement of central components that are prone to tear and wear. However, the actual cost-optimal solution regarding components to be changed versus lifetime will depend on the tear and wear of the individual turbine. However, a generic remanufacturing model has been developed and proposed, which is applicable to a specific turbine model. However, the learnings and methodology could be applied to more models. Life cycle assessments show a strong correlation between lifetime extension and environmental impact reduction in terms of CO_2-eq. emission per kWh delivered to grid.

Slowing of the loops can also be related to component exchange and upgrades as shown in paper II. By installing technologies, that are developed after the commissioning of the turbine, on the turbine, the value increases as a more efficient turbine are now in place with higher energy output. Such modifications hold the potential to increase the ***technical and economic*** lifetime. Further, higher efficiency lowers the environmental impact, when the higher efficiency outweighs the added input as also shown in the case chapter 7. The part provides a generic framework for measuring sustainable value creation in different sectors and of different products.

By assessing h*ow lifetime extension of wind turbines through servitization and remanufacturing can drive sustainable value creation* it was found, that slowing of the loops holds the potential to generate revenues in the aftermarket through various options e.g. upgrade of the turbine (software or hardware), life-time extension programs or even remanufacture activities. Further, these aspects was linked with less environmental impacts as well as job creation. Slowing of the loops can address both turbines with technical and economic lifetimes that comes to an end. Further, slowing the loop strategies have traditionally had the highest margins.

Part IV addressed the closing of loops through a series of case studies.

Paper 3 seeks inspiration on how recycling initiatives have been supported in other industries. It was found that industry examples from automotive, shipping and aircraft on material and environmental information gathering and sharing could support a transition to higher recycling rates.

Decommissioning and recycling of the wind turbines were addressed as part of closing the loops. In the paper, it was found that most parts of the turbine are recyclable, but composite material parts as well as NdFeB magnets constituted a challenge. In an assessment of the impact of recycling a 60MW wind farm, it was found that 81.36GJ of energy was saved by re-introducing the materials into the market compared to primary materials as well as 7351 ton of CO_2-eq.

Composite material continues to be the preferred material among wind turbine blade manufacturers for blade production. The findings from the GENVIND project shows that closed loop recycling of these materials is not expectable in the short-term future under current waste legislation scenarios. The recoverable materials have a too low value compared to the cost of extracting these – although technical possible. However, the project also showed that utilizing the properties of the product or material can beneficial. In closing the loop in the circular economy, upcycling is a common term used. Stenhilper (2014), Sinha et al (2016) and Sung et al. (2014) identify upcycling activities around both products and materials. Material-level upcycling is, in essence, an extension of recycling where materials such as polypropylene can be upcycled into graphene flakes (Gong et al., 2014), or plastic wastes can be upcycled into carbon nanomaterials (Bazargan & McKay., 2012). Alternatively, informal product-level upcycling focuses on creative adaptations of used materials and products in an effort to render a higher value product. The GENVIND project showed attempts of this by e.g. building bridges, play grounds etc. of end-of-life blades (product-level) or using shredded material in new products (material-level). However, the idealistic dream of closed-loop recycling and upcycling is not assessed realistic at the moment, when dealing with composite materials, based on the findings from paper 5.

Regarding NdFeB magnets, the empirical study in paper 6 showed that this could be optimized both in the performance, the supply chain and that increasing the recycling percentage from the world average of <1%. There are several recycling technologies available at lab scale, so developing these to actual recycling plants will be central to ensuring recycling at end-of-life. The study showed that the magnets are large, large volumes are present and they are dismountable. Further, the salvage value, at the time of study, was 11-12 $/kg. The cost of demagnetizing, dismantling and transporting constituted approximately one third of this. Life cycle assessment described in the study also showed that by recycling the NdFeB magnets, production steps including large amounts of acid and energy could be avoided thereby 'short-tracking' the production loop and having magnets with less impact as an outcome. Closed-loop reuse for new turbines were however not possible due to design requirements.

By assessing, *the potentials of closing the loops in terms of value creation*, experiences from other industries showed that supporting the end-of-life with data on materials could increase the level of recycling and thereby provide environmental impact reductions. Further, there are considerable amounts of materials that can be recovered from wind farms with associated embedded energy. However, the economic incentives for optimized recycling are less clear-cut as the monetary impact on the LCOE is insignificant, so the main incentive lies within the environmental impact and the potential associated branding gains from this.

In conclusion, narrowing of the loops has proven essential to minimize the cost of the wind turbine to lower LCOE and also the environmental impact of the turbine. Slowing the loops is two-folded. Service/maintenance is an integrated strategy of the business (and has been for long), whereas refurbishment and remanufacture activities has only recently been targeted by the manufacturers and holds the potential to increase both the economic and technical lifetime of the existing fleet of turbines. Regarding closing the loops, large percentages of the turbines are recyclable. However, composite material remains a challenge, whereas recycling of NdFeB magnets looks promising. So far, no industry or manufacturer initiatives has been developed to support recycling at end-of-life e.g. by providing as material information similar (in product passports) similar to other industries.

Via a set of case studies the analysis has showed how each of the loops defined in the conceptual model can contribute or not to sustainable value creation in the contextual setting. The case studies address different steps of the lifecycle of the wind turbine and can thus be seen as a continuation of cases regarding one lifecycle. However, this is not the case. Each of the cases must be evaluated individually and constitutes then to individual pieces of the understanding of the puzzle 'circular economy and the wind industry.' Each of the cases is analyzed within its own context (e.g. time period, technology choice, geographical setting, etc) and the interplay between the cases has not been analyzed.

12.1.1 CIRCULAR ECONOMY AS A STRATEGY FORSUSTAINABLE VALUE CREATION IN THE WIND INDUSTRY

Wind energy constitutes one of the most attractive renewable energy in terms of price and environmental impact. With the change in in auction-based wind schemes in many countries, the focus on LCOE will continue. This will also set requirements to the ability to 'narrow the loops'. However, the focus should be expanded to not having an insular focus on the turbine itself, but also sub-structures like e.g. the DISTINCT project, which aimed at developing calculation methods for foundations to minimize the material use in the substructure (Siemens Gamesa Renewable Energy, 2018) or modes of transport like e.g. RoRo vessel (Siemens, 2016) or airships (Energiwatch, 2018).

Slowing of the loops will remain central, when LCOE is decreasing. The price pressure and technology advances in wind turbine technology moves this towards a commodity with small margins, whereas the service activities remains profitable with margins in the range of 20% (SGRE, 2018). Managing the wind turbines to operate efficiently and in an optimized manner will continue to support integration of wind energy, where concepts like digital twin (Siemens, 2017), autonomous inspection

(Offshorewind.biz, 2017) and predictive maintenance through machine learning will be key concepts.

The main challenge in terms of closing the loops remains the composite parts, and this needs to be addressed either by developing end-of-life solutions or developing new materials, which are recyclable, to use in the manufacture of the blade.

If these conditions are met, wind energy can contribute to a sustainable, circular economy. However, the adoption of renewable energy must also be perceived from a system perspective and the traditional manufacturing and servicing business model must be rethought in the future. Electrification of the energy system (to increase the demand for electricity) and storage solutions – from batteries (BBC, 2017) to thermal energy storage (Siemens Gamesa Renewable Energy, 2018) – to supply the electricity, when it is needed are business areas to consider to support higher penetration rates of wind energy in the energy systems.

12.2 RECOMMENDATIONS

12.2.1 NARROWING

Narrowing of the loops has proven to be cost-effective and beneficial from a LCA perspective (from 6MW to 8MW). This is depending on potential for upgrade of components like e.g. the magnets, which were apparent in the case from upgrade from 6MW to 7MW to 8MW platforms. Increase in magnet grades will have the potential to further increase the performance of the turbine. However, another topic that became apparent, when assessing the magnets was the potential to increase performance, when operating at lower temperatures while also decreasing or eliminating the need for dysprosium.

Therefore, for future research it could be interesting could expand the research into assessing not only the magnets, but also the interplay with the segments. When operating at low temperature, the efficiency of the generator will improve and the potential for using superconducting materials becomes a possibility. Further, cooling of the segments in the stator will cool the magnets, eliminating the need for dysprosium and creating temperatures for optimal performance (no losses). In general, this holds the potential for higher efficiencies in the electrical drive train, higher AEP and importantly, a lighter generator (which will impact on balance of plant, transport etc). This will increase the costs for cooling significantly, but the this might be outweighed by the increase in production and savings in terms of size. This topic requires further technological research for developing the technology, business research to calculate the LCOE of the potential and supplemented with LCA data to explore the environmental impact of this solution (no dysprosium, cooling requirements, replacing copper with superconducting material, decrease in mass etc).

Further, from an academic point of view, researching the relationship between LCOE and LCA results could be interesting assuming that the LCOE implies material use, embedded energy, etc. to assess the correlation between the two concepts. Moreover, it could be interesting to assess whether less data-dense KPIs could be established to measure the 'eco-effectiveness' of the product e.g. top mass (nacelle including rotor) per MW(h) or what is needed to have an 'easy' assessment guideline that could guide the future development.

In short, the recommendations are:

- Development of improved efficiency generators to narrow loops
- Establish KPIs to guide 'narrowing' of the loops
- Research the relationship between LCOE (cost) and LCA (environment)

12.2.2 SLOWING

Different potentials for slowing the loops are worth investigating.

An already established project at the company, which will be carried into the future is the aim to develop and demonstrate and O&M information management platform, which intends to improve the decision-making process in order to reduce the O&M costs, improve reliability and extend the lifetime of offshore wind turbines and wind farms. (European Commission, 2017) The project aims at providing a better understanding of the real-time behavior of the main components of the wind turbines under operating conditions, and thereby maximize the lifetime and reduce the need for maintenance. (European Commission,2017)

Development of servitization concepts (such as autonomous drones for blade inspection or new diagnostic models) or digitalization concepts (such as optimized fleet performance) will be central in reducing the OPEX and increasing the AEP in the future. Decreasing the visits to the turbine (especially offshore) will be a driver of LCOE reductions.

Aftermarket modifications and upgrades that can be applied to the existing fleet of wind turbines already installed worldwide in order to increase the output from these and thereby the value of these assets is an opportunity addressed, which could be further expanded. This could include new converters (to meet grid compliance requirements), control systems (for optimized management of the turbine and thereby higher energy output) or even concepts blade tip extension could be relevant to research further for the OEM – and how these could support each other for optimized energy production.

Finally, a thorough evaluation of the business case, from the OEM side, for full-scale remanufacturing of the existing installed fleet, when they reach their end-of-service-life at one site, is needed. This includes technical evaluation of each of the components, economic evaluation of the turbine in order to be price competitive, an environmental assessment highlighting the impact and a measure of the potential social implications for these (potentially) low cost wind turbine models in order to create sustainable value.

In short, the recommendations are:

- Research on optimizing component lifetimes
- Research on servitization and digitalization concepts
- Research on aftermarket opportunities for optimized or increased production
- Research on the potential of full remanufacturing for sustainable value creation

12.2.3 CLOSING

Closing of the loops is a massive challenge and perhaps the least controllable by the company itself. However, the project shed light on some potentials, which could be further explored and researched.

12.2.3.1 General observations

Decommissioning and end-life-handling have so far gained little attention. However, the project showed benefits of recycling of the wind turbines from an environmental point of view. However, (at least) two interesting questions emerged from the research, which remains unanswered:

As described in paper 4, it is today included in the projects is a requirement to pay a decommissioning bond. This is not necessarily decided based on actual decommissioning costs therefore research into the actual decommissioning costs and potentials for optimization to further reduce the LCOE could be relevant. The research is not necessarily an OEM topic, but of interest to the wider industry to reduce the LCOE.

Second, this project included research on how other industries approached supporting recycling at end-of-life by collecting and providing data on the materials contained in the product. This was explored through the use of ‘product passports’. Simultanously, during the time frame of the project, the concept of Blockchain has become more and more apparent, and for further research the link between Blockchain technology and end-of-life data support could be an interesting area of exploration.

In short, the recommendations are:

- Research on the effects on LCOE by integrating decommissioning considerations earlier in the design phase

- Research on the link between data management through Blockchain technology to support end-of-life management

12.2.3.2 MAGNETS

The research and development related to magnets will certainly continue as long as the direct-drive technology remain central in the offshore strategy of the company. The suggestions on slowing and closing will not address the topics of stronger magnet grades (less material use per energy output), shift of generator technology or use of magnets without rare earth elements, but provide suggestions based on today's situation.

The practical tests of demagnetization and use of these in new magnet production provides some insights into potential next steps. These learnings could beneficially be coupled with expertise from relevant stakeholders in this field. As mentioned in paper 6, the EU have pointed out a range of critical materials, where the magnets play an important role. This have led to a series of research networks e.g. ERECON, REMANENCE, REProMAG, EREAN, DEMETER and SCRREEN, which all have different objectives, but all related to addressing different aspects of recycling rare-earth materials to keep these within the EU and thereby decrease the sourcing risks. From a company perspective, it does also make sense to secure a stable supply in the future.

However, these projects have never addressed the magnets in the wind turbines beyond a theoretical perspective, Therefore, practical experimentation with the specific challenges related to this topic will further expand the knowledge on 'circular magnets' and could contribute to advance rare-earth recycling to a technology readiness level.

In short, the recommendations are:

- Research applying identified recycling technologies on magnets from wind turbines

12.2.3.3 Blades

The challenge of having 'circular blades' was advanced by the participation in the GENVIND project with potential recycling routes that could be further researched deriving from that one. From a company perspective this is being approached by the participation in the FibREuse project, which intends to find secondary applications for the composite material through mechanical recycling. This is an strategy to advancing the potentials on the blades already installed. However, as pointed out in paper 5, handling the thermoset plastics in a composite mixture will remain a challenge. This is difficult to solve on lab-scale experiments, and will probably remain challenging in remote areas. The recommendation is to engage in development of e.g. a thermoplastic material that can be utilized in the blades acknowledging the strict specifications these needs to meet.

In short, the recommendations are:

- Engage in research on developing e.g. thermoplastic material to use in blades to improve recycling.

12.2.4 COLLABORATING

A final remark is on collaborating and communicating with stakeholders such as customers. One additional paper (paper 7) was developed as part of the PhD project. This analyzed how sustainability were communicated from SWP to its customers and how the customers could be engaged for sustainable value (co)creation. It was found that the topic of sustainability is increasingly important and that there is a change from traditional HSE in operations to sustainability over the full life cycle(s). The paper found that extended producer responsibility was one identified strategy that OEMs could adopt whereby they widen their scope of responsibility and 'shake' other industry stakeholders. Open forms of communication, participation in networks and strategic partnerships could help to advance common sustainability goals and foster mutual benefits related to innovation and value creation if embraced by the OEM, its O&M customers and other stakeholders throughout the value chain. This is true in the wind power sector where collaboration is revered as key to increasing the future share of renewables. Relating back to addressing the system perspective, an open, close collaboration is recommendable as some of the challenges in slowing and closing the loops is involving both the manufacturer and its customers.

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APPENDICES

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